9950-330

PHASE I OF THE NEAR TERM
HYBRID PASSENGER VEHICLE DEVELOPMENT
PROGRAM

Contract No.
955197

FINAL REPORT

Prepared for
JET PROPULSION LABORATORY
by
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The research described in this publication has been carried out by C.R. FIAT under JPL contract No. 955187. This report is divided into two parts:

Part I giving a general description of the activities carried out to fulfil contractual requirements and the results obtained

Part II giving information on specific topics related to the performed program.

Turin, September 21, 1979

This Report has been prepared by:

P. Montalenti and R. Piccolo of CRF

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ABBREVIATIONS AND GLOSSARY

In the text Metric System standard units and related abbreviations have been extensively used. Other units such as mile gallon etc. have also been used in the text. A list of their abbreviation is given below together with the various achronims used in the text.

A	=	Frontal Section Area
α	=	$\frac{\text{Thermal Power}}{\text{Total Power}}$
AC	=	Alternating Current
APR	=	Annual Percentage Rate
c	=	Cent
C_x	=	Aerodinamic Drag Coefficient
CAFE	=	Corporate Average Fuel Economy
CID	=	Cubic Inch Displacement
CVRT	=	Continuously Variable Ratio Transmission
DC	=	Direct Current
DOD	=	Depth of Discharge
DOF	=	Degree of Freedom
EPA	=	Environmental Protection Agency
FC	=	Full Capital
FHDC	=	Federal Highway Driving Cycle
FMVSS	=	Federal Motor Vehicle Safety Standards
FUDC	=	Federal Urban Driving Cycle
gal	=	Gallon
HP/HP	=	High Power/High Profile
ICE	=	Internal Combustion Engine
K_n	=	Tire Rolling Resistance Coefficient
L	=	Lira
Lb-ft	=	Pound - Feet

M	=	Mutual Inductance
min	=	Minute
mi	=	Mile
MPG	=	Miles per Gallon
NTHV	=	Near Term Hybrid Vehicle
OBC	=	On Board Computer
RPM	=	Revolution per Minute
SAE	=	Society of Automative Engineer
SI	=	Spark Ignition
τ_d	=	Differential Ratio
τ_1, τ_2, τ_3	=	Gear Ratio
V_N	=	Battery Voltage

FOREWORD AND ACKNOWLEDGEMENTS

This Report on the "Phase I of the Near Term Hybrid Passenger Vehicle Development Program" is the result of a joint effort between Centro Ricerche FIAT (CRF) S.p.A. (FIAT Research Center) and the following Subcontractors:(1)

- Brown Boveri & Cie A.G. (B.B.C.) (Na-S batteries)
- Illinois Institute of Technology - Research Institute (IITRI) (Mission Analysis)
- (Fabbrica Italiana) Magneti Marelli S.p.A. (Lead-Acid and Ni-Zn batteries, electric motor and power conditioner)
- Pininfarina S.p.A. (Body styling)
- Pirelli S.p.A. (Tires)

The Authors wish to express their appreciations to Messrs. Bogetti, Castelli, Dotti, Frondaroli, Ippolito, Leonardis, Pellegrino, Rinolfi, Tornatore, Vittone and Zucchelli of C.R. FIAT and their staff who made the essential contribution to the study development, to Messrs. Morello and Brusaglino of C.R. FIAT for their advice and support to the program efforts, to Mr. Sandberg of JPL and to Mr. Traversi of C.R.FIAT for their contribution for the draft's revision, as well as to Messrs. Vercelli of C.R. FIAT, Antoniotti, Fiandrotti, Garavana and Guerci of SCL-SIPAL and their staff for their effort in the final editing and typing of the Report.

(1) Additional data on Ni-Zn batteries have been kindly provided by Could in support of the Phase II Proposal preparation.

PART I

GENERAL DESCRIPTION OF PROGRAM ACTIVITIES

S E C T I O N 1

INTRODUCTION, CONCLUSIONS AND RECOMMENDATIONS

There is little disagreement between energy and transportation analysts regarding the basic long term outlook for petroleum saving. Recent legislation contained in the Energy Policy and Conservation act of 1975 has already resulted in downsizing of vehicles to meet the mandatory fuel economy standards. Further reduction of petroleum consumption by passenger vehicles could be achieved by reduction of energy waste and/or use of alternative energy sources:

- by reduction of vehicle size: this solution is possible as it has been shown that most commuter missions are carried out with a low level of occupancy. Small vehicles, however, cannot meet the requirements of other types of missions (social, recreation etc.) characterized by higher levels of occupancy which result, incidentally, in "per passenger" petroleum savings.
- by use of electric vehicles: these can be used for all missions characterised by a total range which is both limited and known, such as commuter missions. Electric vehicles cannot be used on the other hand for longer missions, for business or recreational purposes, where the range cannot be predicted with certainty.
- by use of hybrid vehicles: these combine the traction power of an internal combustion engine and an electric motor, supplied by liquid fuel and the battery respectively; they can offer, in lation to their system architecture, sizing and control strategy, a wide variety of solutions.

JPL requirements for the near term passenger hybrid vehicle called for performance figures comparable to those of a conventional vehicle in terms of speed, acceleration and range, combined with a significant reduction in fuel consumption. The results achieved during the activities carried out, covered by the Phase I of the JPL program, show that the requirements set

can be best met by a full size, general purpose vehicle with a competitive purchase price and an operational cost substantially equal to that of a conventional vehicle.

The six passenger sedan proposed, in order to meet project requirements and be competitive in the 1985 market, incorporates:

- a high power type Ni-Zn battery which, by making electric-only traction possible, permits the achievement of an optimized control strategy based on electric-only traction to a set battery depth of discharge, followed by hybrid operation with thermal primary energy. This results in a high efficiency of the hybrid propulsion subsystem
- all the technical solutions, available at FIAT, which aim to contain energy waste by reducing vehicle weight, rolling resistance and drag coefficient.

Replacing new 1985 full size vehicles of conventional type by hybrids of the proposed type would result in a U.S. average gasoline saving per vehicle of 1,261 liters/year (because 561 liters/year are consumed by the hybrid against 1,822 liters/year are consumed by the new 1985 conventional) and an average energy saving per vehicle of 27,133 MJ/year. Continuation of the hybrid vehicle development effort is therefore recommended, as one of the main lines to be followed to reduce overall U.S. petrol consumption.

S E C T I O N 2

SUMMARY OF CONTRACT ACTIVITIES

2.1 INTRODUCTION

In general, the activities covered by the JPL Phase I "Near Term Hybrid Vehicle Program" contract have been performed by C.R. FIAT in accordance with JPL'S statement of work. However, some of the activities included in the Task 2 (Trade-off Studies) concerning the selection of key components and control strategies have been performed during the Task 3 (Preliminary Design) effort, while part of the Preliminary Design activities have been brought forward to earlier stages of the project. Such a decision was a result of previous C.R. FIAT experience in advanced vehicle development; it is, in fact, more appropriate to define some basic design aspects at the very beginning of a project, while final selection of key components can only be made when a fairlv well-advanced vehicle design stage has been reached.

The activities performed are briefly summarized below.

2.2 DESCRIPTION OF THE PERFORMED ACTIVITIES

All the performed activities were based upon the contractual statement of work, taking into consideration the constraints and minimum requirements, as well as on the assumptions and guidelines given by JPL at the beginning of the Phase I effort.

2.2.1 Mission Analysis and Performance Specification

The Mission Analysis commenced with a projected assessment of the U.S. fleet in 1985, divided into vehicle and mission classes. Then the performances and typical missions applicable to the hybrid vehicle were defined and the reference conventional vehicle, used as a bench mark for the hybrid vehicle evaluation, was identified. Finally, an outline specification of the vehicle was issued, in terms of:

- size (number of passengers, payload, passenger compartment and trunk volume)
- performance (acceleration, cruise and top speed, gradeability)
- reference mission (or cycle)
- handling
- reliability
- availability.

The following more detailed activities were performed:

- Mission Analysis, consisting of categorization and processing of applicable data according to vehicle usage including climate, environment, terrain, population, etc.; analysis of trips (ranges, frequency, purpose, etc.) and trip parameters (acceleration, cruise speed, grades, etc) with consideration of payload (cargo, people, size) and including applicable driving cycles; development of a mission matrix that includes indices of measurement (range, time, cargo, etc.), parameter distribution, driving cycles, etc., in terms of vehicle usage taking into account overlapping of missions; estimation of potential fleet size for each of the quantified missions; formulation of the driving cycle combination that represents the quantified missions, and selection of the mission that maximizes the fuel saving potential for the total vehicle fleet.
- Vehicle Characteristics Study, consisting of identification and formulation of those considerations based upon mission requirements that have a bearing on conventional and hybrid vehicle performance and characteristics; analysis and trade-off study of vehicle performance and characteristics in terms of mission requirements; analysis of performance and characteristics of candidate reference vehicles in terms of parameters and trade-offs; analysis of annual Fuel Consumption in terms of mission; selection of a reference conventional ICE vehicle that meets or exceeds all mission and minimum vehicle requirements while remaining within applicable constraints.
- Vehicle Performance Specifications, consisting of identification and formulation of updated considerations based upon the mission

requirements and the impact of the selected reference vehicle performance and characteristics; analysis of candidate hybrid vehicle performance and characteristics in terms of mission requirements, mission-related vehicle characteristics, fuel consumption, etc. and the generation of vehicle performance specifications for the hybrid vehicle.

A summary of Mission Analysis results is given in Table 2.2-1; the values shown are referred to the average General Purpose mission performed by the projected 1985 large size passenger vehicles from all car-owuing households (average household with car).

The vehicle size clan/mission distribution was performed for the average household only, while the vehicle/mission distribution was performed for each group of households (1, 2 or more cars/household).

The Vehicles used in the General Purpose mission M_3 were found to exceed 50% of the total fleet (55.7%): about 36% of these general purpose vehicle were found to be full size cars and about 30% intermediate size cars.

The full size cars used for general purpose mission were found to account for over 23% of the total fleet fuel consumption (about 39% of the general purpose fleet fuel consumption): the corresponding figures for intermediate size cars are about 19% and 31%. The projected 1985 Chevrolet Jmpala car was accordingly selected as full size reference vehicle. More specific reference was made to the 1978 Lancia Gamma characteristics as being the passenger vehicle in the present FIAT fleet which more closely match the projected characteristics of the U.S. full size 1985 model year.

A summary of the most relevant vehicle performance specifications is given in Table 2.2-2 (second column); they all meet or exceed, as applicable the minimum requirements originally set by JPL (first column). The minimum non refueled range specifications have been set with reference to the 95th percentile

TABLE 2.2-1
M3, K5 MISSION SPECIFICATIONS

No.	PARAMETER	VALUE	COMMENTS
M1	DAILY TRAVEL, MILES (km) MILES (km)	20 (32) 142 (227)	50 TH PERCENTILE (1) 95 TH PERCENTILE (1)
M2	PAYLOAD, kg (PASSENGERS + CARGO)	350 – 50 400 (TOTAL)	95 TH PERCENTILE 4,15 PASSENGER OCCUPANCY (2)
M3	TRIP LENGTH, MILES (km) TRIP FREQUENCY, TRIPS PER DAY TRIP PURPOSE, MISSION	11.0 (17.6) 3.4 M3	MEAN (ONE WAY) MEAN (PER VEHICLE) GENERAL PURPOSE (URBAN/SUBURBAN/INTRAURBAN)
M4	DRIVING CYCLES, (REFERRED TO DAILY TRAVEL)	S U H – 4 10	SEQUENCE: U, 5H, 2U, 5H, U (3) 95.5 PERCENTILE (149 MILES)
M5	ANNUAL TRAVEL, MILES (km) MILES (km)	13,300 (21,300) 35,500 (56,700)	MEAN (PER VEHICLE) 95 TH PERCENTILE (4)
M6	VEHICLES IN USE, MILLIONS OF VEHICLES (%OF FLEET) (%OF K5 CLASS)	22.6 (20.0) (91.0)	TOTAL FLEET: 113,2 MILLIONS VEHICLES TOTAL K5 CLASS: 24,9 MILLIONS VEHICLES
M7	REFERENCE CONVENTIONAL ICE VEHICLE	K5	AVERAGE NEW 1985 LARGE AUTOMOBILE
M8	FUEL CONSUMPTION, GALLONS BILLIONS OF GALLONS (%OF TOTAL) BILLIONS OF GALLONS (%OF TOTAL) BILLIONS OF GALLONS (%OF TOTAL)	480 46.4 (100) 10.9 (23.5) 28.2 (60.7)	K5 REFERENCE ICE VEHICLE (SINGLE M3 MISSION) ALL REF. ICE VEHICLES (ALL MISSIONS) K5 REF. ICE VEHICLES (K5 FRACTION OF ALL M3 MISSION) ALL REF. ICE VEHICLES (ALL M3 MISSIONS)

(1) CUMULATIVE PERCENT OF DAYS
(2) CUMULATIVE PERCENT OF TRIPS (2 MALES 95 TH PERC. + 2.15 MALES 50 TH PERC.)
(3) S – SAE, U – FUDC, H – FHDC
(4) CUMULATIVE PERCENT OF K5 VEHICLES IN M3 MISSION

From Appendix A - Mission Analysis and Performance Specification Studies - Volume I, Final Report, Table 5-1 page 5-11.

TABLE 2.2-2

MINIMUM REQUIREMENTS AND PERFORMANCE SPECIFICATIONS/PROJECTIONS

ITEM		MINIMUM[1] REQUIREMENTS	1985 ICE VEHICLE SPECIFICATIONS	NTHV
MINIMUM NON-REFUELED RANGE				
FHDC	(km)	NS[2]	270[3]	975[4]
FUDC	(km)	NS	190	713
SAE J227a (B)	(km)	NS	145	479
SPEED CAPABILITY				
Cruise	(kph)	90	105	120
Maximum	(kph)	NS	120	130
Time max. can be sustained	(min)		2	–
ACCELERATION TIMES				
0-50 kph (0-31 mph)		6	6	5.5
0-90 kph (0-56 mph)		15	15	13.8
40-90 kph (25-56 mph)		12	12	9.5
GRADEABILITY				
Speed on 3% grade	(kph)	90	90	90
Distance	(km)	1.0	8.0	(5)
Speed on 5% grade	(kph)	72	72	72
Distance	(km)	0.3	3.2	(5)
Speed on 15% grade	(kph)	25	24	25
Distance	(km)	0.2	0.8	(5)
Maximum grade	(%)	NS	20	40
PAYLOAD				
No. of Passengers		5	6	6
Cargo capacity	(m^3)	0.5	0.57	0.57
Total Payload	(kg)	520	545	545
CONSUMER COSTS				
Purchase price	(1978 $)	–	9,046	10,974
Life cycle cost	(1978 ¢/km)	–	14.4	14.7

(1) MINIMUM REQUIREMENTS SPECIFIED BY JPL

(2) NOT SPECIFIED

(3) ON 21 LITERS (MISSION DAILY RANGE REQUIREMENTS)

(4) ON 40 LITERS

(5) SPEED GIVEN IS MAINTENABLE ON HEAT ENGINE ALONE SO DISTANCE IS LIMITED ONLY BY TANK CAPACITY.

of the daily-distance distributions: such values were to be largely exceeded by projected NTHV range capabilities as shown in the third column.

It is worth noting that the fleet of general purpose cars would be split as follows: 35% in 1-car households, 47% in 2-car households and 18% in 3 or more-car households.

The corresponding splitting of the total fleet is projected to be 21%, 52% and 27%.

2.2.2 Trade-Off Studies

Once the principal characteristics of the vehicle were defined, the Trade-Off activities were performed, consisting of the competitive evaluation of different configuration and key component solutions. The alternative solutions were analysed in the light of their impact on vehicle characteristics, namely:

- weight
- fuel and energy economy
- performance
- initial and life cycle cost.

As far as the hybrid propulsion system configuration is concerned, several alternatives were examined, consisting of various parallel hybrid configurations characterized by the use of a Continuously Variable Ratio Transmission (CVRT) on the ICE only or on the whole propulsion system, and of a conventional clutch.

As far as the battery is concerned, the Trade-Off was performed comparing a vehicle equipped with a Lead-Acid battery against a vehicle equipped with a Sodium-Sulphur battery, thereby representing the full spectrum of batteries expected to be available in the mid eighties, in terms of the energy density effect on hybrid operation mode and energy/fuel economy. Finally the general layout of the vehicle was defined together with the principal vehicle design features. A front wheel drive, transversally mounted propulsion system was chosen in association

with a steel frame integrated with plastic panels, constituting the basic C.R. FIAT approach to the vehicle design.

The various alternatives have been compared using the "SPEC 78" simulation program (1) as far as the performance, consumption and emissions evaluation is concerned.

Other parameters such as production and operating costs, availability, have been evaluated on the basis of current methodologies used in FIAT (2).

The step-by-step analysis process used for the various alternatives evaluation is described in Subsection 3.1.2 of Appendix B. Trade-off studies, Volume I, Final Report, pages 3-5 through 3-8.

2.2.3 Preliminary Design Data Package

During the Preliminary Design two types of activities were carried out in parallel. On one hand the selection of the control strategy and the key components was completed, starting with the selection of the battery. On the other hand the Preliminary Design was implemented. The design reached a high degree of detail for several of the alternatives considered, as the comparison between optimised system designs was often the only way to assess the superiority of one solution against another.

As far as the control strategy is concerned, suitable strategies were identified and evaluated for each configuration considered and the optimization task was performed taking into account the different behaviour of each type of battery.

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(1) See Section 6 below and TRADE-OFF Studies - Volume II Appendix A.3-1 page 1.3-1.

(2) See TRADE-OFF Studies - Volume I Methodology Description 3.2.3.1 page 3-12.

The Hybrid Vehicle preliminary design was performed at two different levels: layout level, to define the general configuration of the vehicle body and structure and of the propulsion system; component level, to support the above activities (detailed study on structure, handling and crash analysis, overall component definition) and to define, in accordance with the specific Preliminary Design requirements, the propulsion system and auxiliaries components at a deeper level as appropriate (battery, electric motor and power conditioner, thermal engine, transmission, control system).

A summary of projected performance of NTVH is given in Table 2.2-2 (third column); which meets or exceeds all the reference vehicle performance specifications given on the third column of Table 2.2-2.

As the thermal engine power was established so that the maximum speed could be achieved without any electric power contribution while the electric motor power was established to meet the acceleration requirements in conjuction with the available thermal power, the actual NTHV top speed capability using full hybrid power exceeds the specified maximum speed specified distance on grades at the specified speeds is also largely exceeded due to the fact that such speeds can be achieved u ing thermal power only. The outstanding values of the nonrefueled driving ranges in the various cycles result from the decision to retain the same fuel tank capacity of a corresponding projected 1985 conventional ICE passenger vehicle.

The concluding task was that of providing weight, costs and performance evaluation and projected petroleum and energy consumption.

2.2.4 Sensitivity Analysis

The Sensitivity Analysis of the Mission Analysis, Performance Specification Study and Trade-Off Studies results was performed to

evaluate the influence of the value variation of some significant parameters, namely:

- Number of passenger vehicles and average annual kilometers travelled per vehicle.

  The ±7% variation of the parameters above has a negligeable influence on the reference mission and the vehicle performance specifications are unmodified.

  As far as the influence on the Trade-Off Studies is concerned, only the annual travel has a little impact on the life cycle costs, regardless of the design solution adopted.
- Gasoline and diesel prices and electricity price.

  While sensitivity to variation of electricity prices are negligeable, the gasoline price variations (±30%) can modify the life cycle costs of the hybrid vehicle but at a very low level (±2%).

In conclusion no negative considerations arose from this study, while any gasoline price increase would make the hybrid vehicle more competitive with the reference one.

2.2.5 Phase I Activities not Covered by the Task Reports Issued

Other than the activities specifically requested by the contract and completely covered by the task reports issued by C.R. FIAT at the completion of each task two additional studies were performed. One with the purpose of predicting which technological improvements shall be included in the 1985 conventional vehicles to meet JPL fuel economy projections and therefore can be considered commercially available for the 1985 hybrid vehicles. The other with the purpose of assessing the effect of deviation from the proposed design characteristics (weight, drag coefficient and rolling resistance) on hybrid vehicle performance (acceleration and speed, energy and fuel economy).

A more detailed description of the above activities is given in Part II, section 5 of this report.

S E C T I O N   3

VEHICLE DESCRIPTION

3.1 GENERAL DESCRIPTION

The vehicle conceived by C.R. FIAT during Phase I and proposed for development during Phase II of the JPL "Near Term Hybrid Vehicle Program" is a general purpose six passenger, hatchback, five-door sedan with a 0.57 m^3 cargo capacity and 545 kg payload. The vehicle layout is shown in Fig. 3.1-1.

The front wheel drive power train is based on a spark ignition engine and a separately excited DC electric motor powered by a Ni-Zn battery through a power conditioner based on a transistorized power unit. The power train delivers a maximum power to the wheels of 97 HP (about 71 kW) and is capable of propelling the vehicle at a maximum speed of over 130 km/h and a cruise speed of over 120 km/h. The output torque is sufficient to meet all the specified acceleration and gradeability requirements.

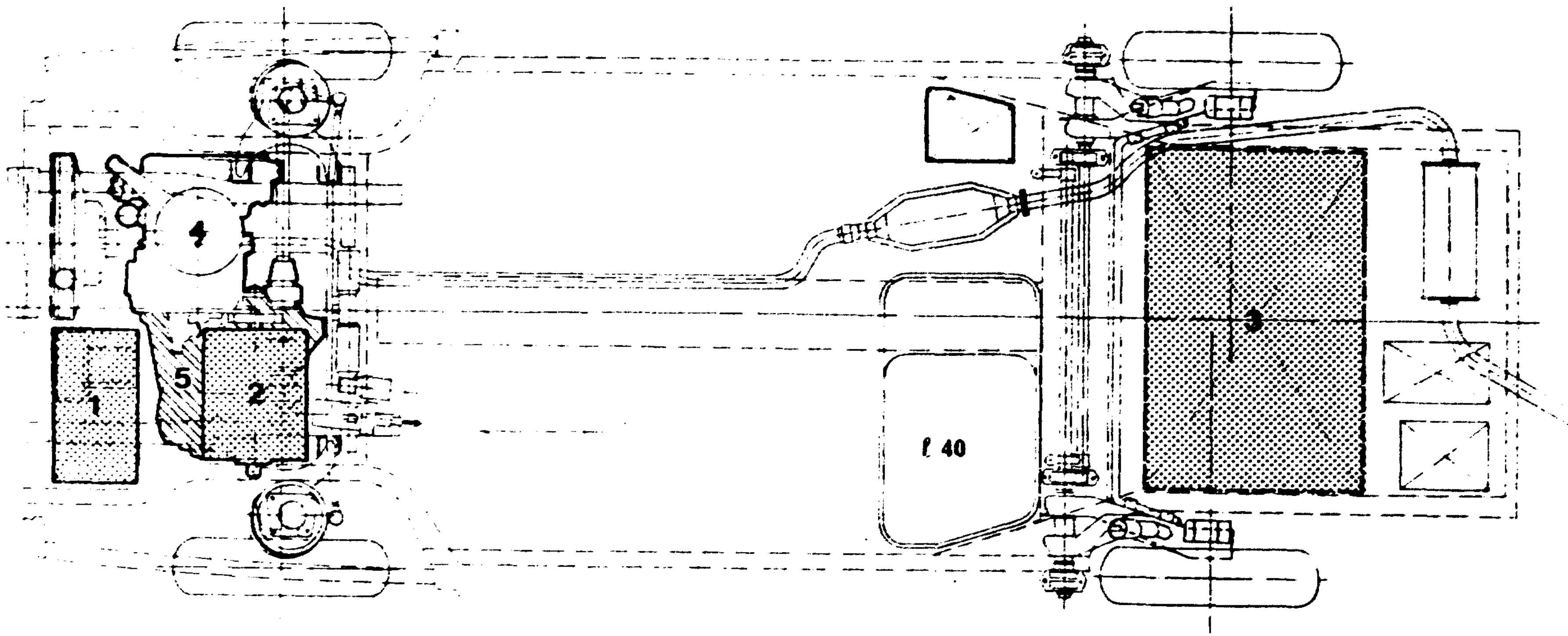
The electric motor, power conditioner and battery are sufficiently powerful to permit electric-only traction both in urban and highway conditions, for ranges up to 130 km, meeting the requirements of the FUDC and FHDC.

The Continuously Variable Ratio Transmission (CVRT), based on a steel belt transmission with lock-up clutch, permits use of the engine at maximum efficiency with mimimum emissions, as well as thermal-only traction in emergency conditions.

The suspension and drive mechanics are characterized by:

- Mc Pherson type front wheel suspensions
- torsion bar rear suspensions
- double circuit, power assisted disc brakes
- power assisted rack and pinion steering system.

Their use in a relatively light (1600 kg) vehicle with balanced weight distribution (860 kg on the front axle, 760 kg on the rear axle), obtained by mounting the whole propulsion train transversally on the front wheels and the battery between the rear wheels under the trunk floor, makes the vehicle handling comparable with that of the reference conventional vehicle of similar characteristics.



1 POWER CONDITIONER
2 D.C. MOTOR
3 Ni-Zn BATTERY
4 INTERNAL COMBUSTION ENGINE
5 CONTINUOUSLY VARIABLE RATIO TRANSMISSION

Fig. 3.1-1 – HYBRID VEHICLE TOP VIEW-PROPULSION SYSTEM INSTALLATION

The vehicle structure is based on a conventional steel frame, largely accounting for the vehicle mechanical soundness and crash resistance, integrated with light-weight glass fiber reinforced plastic fixed and movable panels. The vehicle body design, developed to achieve a drag coefficient $C_x = 0.3$, is shown in Fig. 3.1-2.

The hybrid operation mode selected is implemented by the on-board computer which also provides the monitoring, assessment and protection of:

- the battery
- the electric power subsystem (motor + power conditioner)
- the ICE
- the CVRT.

The fuel and energy economy vs. range achievable by the proposed vehicle are represented in Fig. 3.1-3 and 3.1-4 for an optimal operating mode based on electric only traction until 80% battery discharge, followed by hybrid operation without discharging the battery.

The electric power system, apart from the components already mentioned, consists of:

- the on-board battery charger, using the same power unit included in the electric motor power conditioner
- the auxiliary battery
- the alternator, powering auxiliary equipment and recharging the auxiliary battery during engine operation
- the DC-DC converter, powering auxiliary equipment and recharging the auxiliary battery from the main battery when the engine is not in operation.

The vehicle described above in general terms should have a competitive purchase price and a life cycle cost equal to that of the reference vehicle. Its life cycle energy consumption is significantly lower than that of the reference vehicle. The life cycle gasoline consumption is much lower.

Vehicle subsystems and basic components are described in the following subsection.

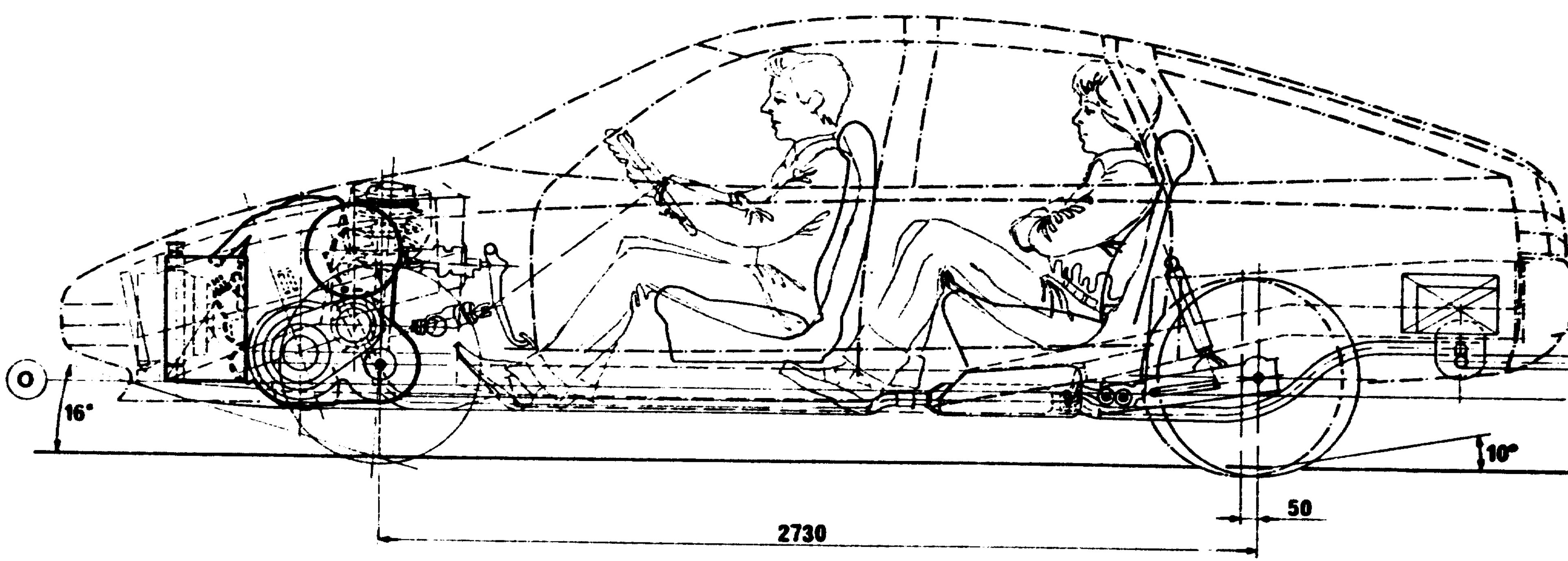


Fig. 3.1-2 – HYBRID VEHICLE-SIDE VIEW OF BODY, PROPULSION SYSTEM AND MISCELLANEOUS COMPONENTS

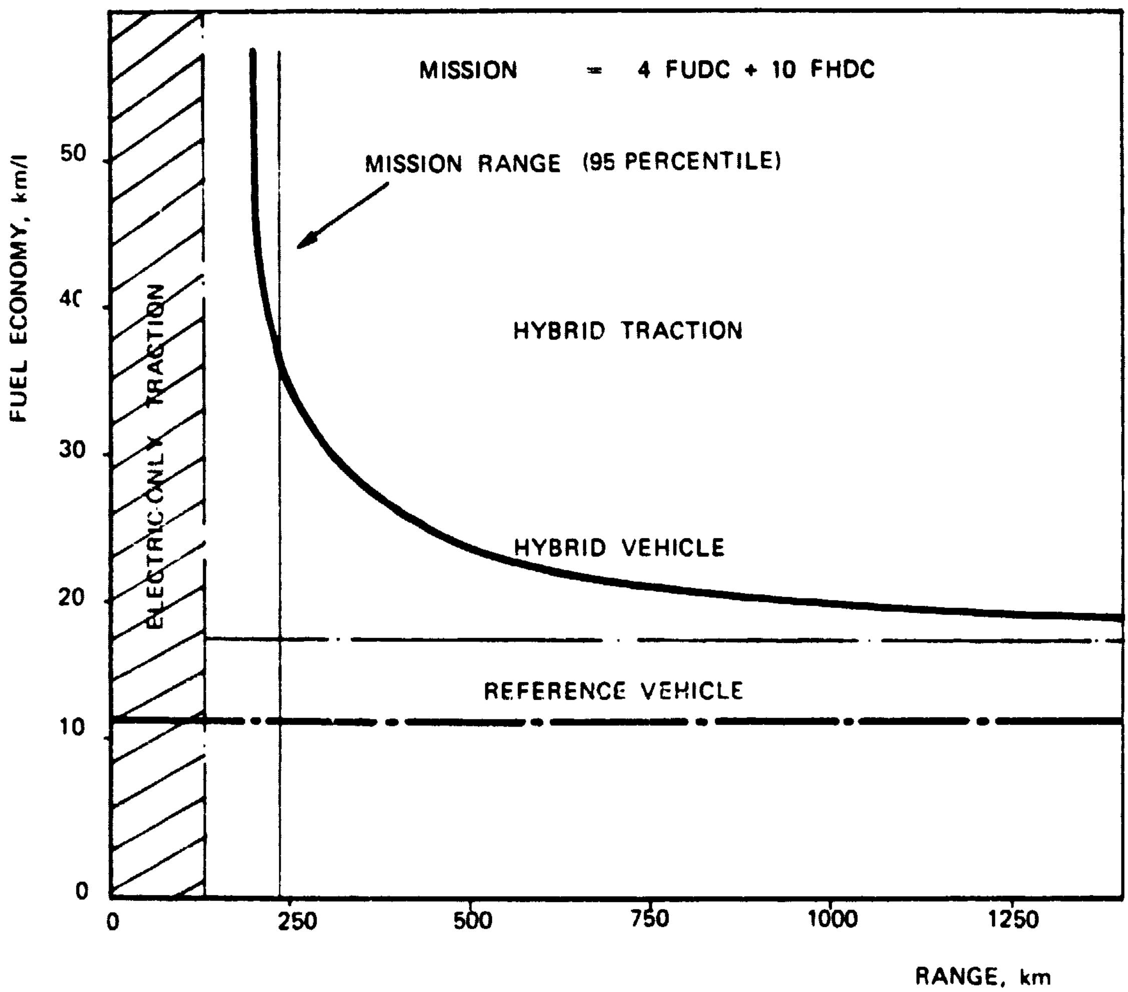


FIG. 3.1-3 - FUEL ECONOMY VS. RANGE

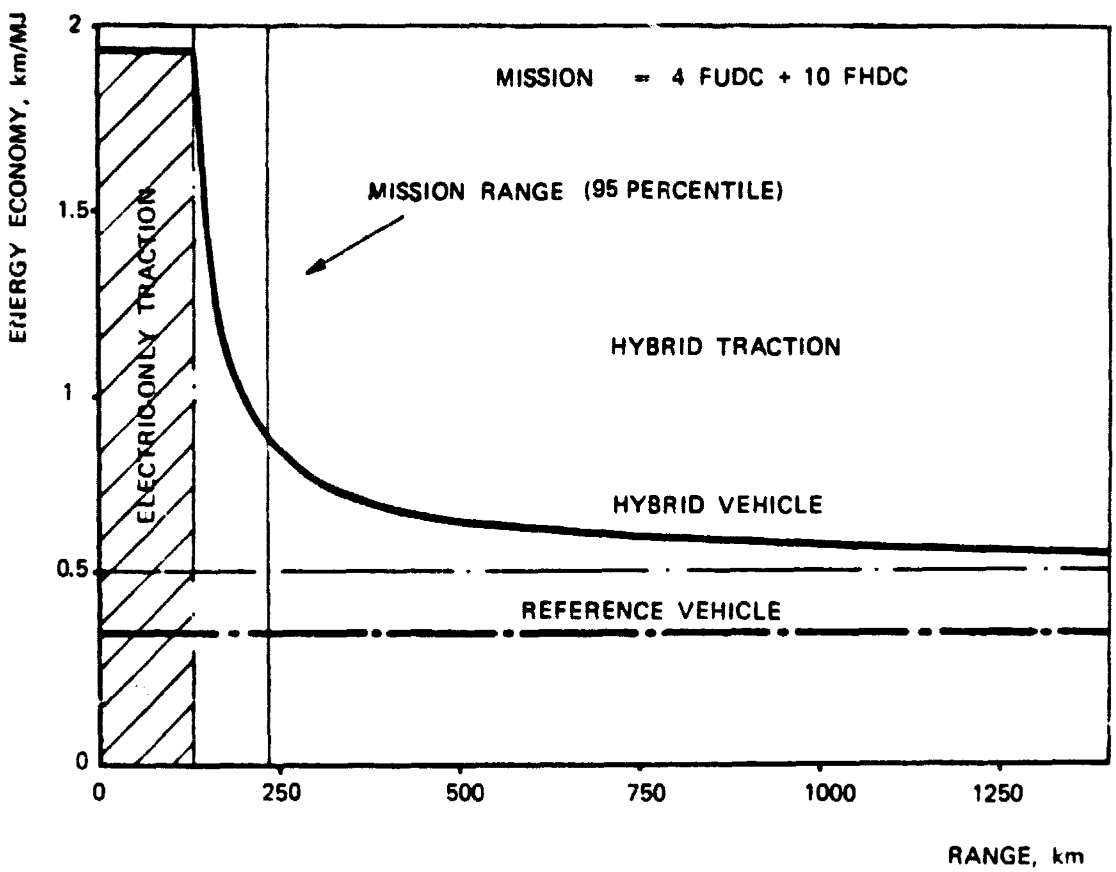


FIG. 3.1-4 – ENERGY ECONOMY VS. RANGE

3.2 THE HYBRID POWER TRAIN

The front wheel drive power train, schematically represented by the sketch of Fig. 3.2-1, is basically formed by an ICE, transversally mounted and titled by 20°, coupled through a torque converter with lock-up clutch and a CVRT to the electric motor; this is directly connected to the differential and trasmission group, as shown by the basic block diagram of Figure 3.2-1A.

The power train is fixed to the body frame using an auxiliary loom. It is electrically powered by the traction battery through a transistorized power conditioner, which is controlled by the on-board computer.

When the engine is operational, it also provides power for the auxiliary devices and heat for passenger compartment warming during the cold season.

3.2.1 The Internal Combustion Engine

The internal combustion engine is a FIAT 138 - 1100 engine with feedback carburetor and automatic control of ignition timing. The main characteristics of the engine are described by Table 3.2-1.

3.2.2 The Electric Motor

The separately excited DC electric motor is characterized by on overall weight of 95 kg, a peak power of 35 kW and a continuous power of 16 kW.

It is basically derived from the of FIAT MT-290 motor which powers several FIAT electric vehicle types.

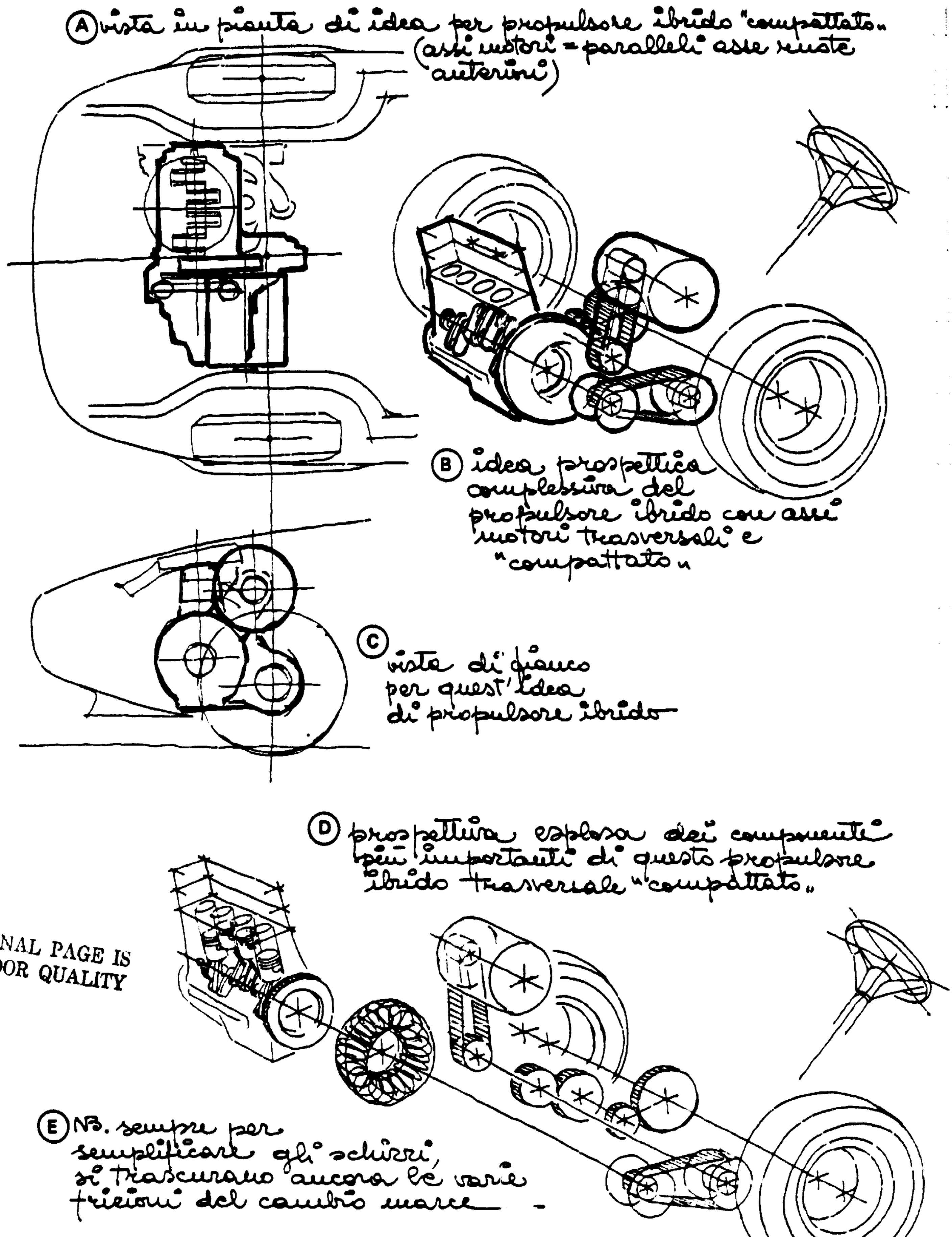


FIG. 3.2-1 – ORIGINAL SKETCH OF PROPULSION SYSTEM STUDY

LEGEND FOR PAGE 3-8 CALL OUTS

A – Top view of proposed "compacted" hybrid propulsion system (the driving axles are parallel with the front wheel axle)

B – Overall perspective view of proposed "compacted" hybrid propulsion system with transverse driving axles.

C – Side view of proposed hybrid propulsion system.

D – Exploded perspective view of the "compacted" transverse hybrid propulsion system basic components.

E – For simplicity reasons, the various transmission clutches have not been shown.

FIG. 3.2-1 – ORIGINAL SKETCH OF PROPULSION SYSTEM STUDY

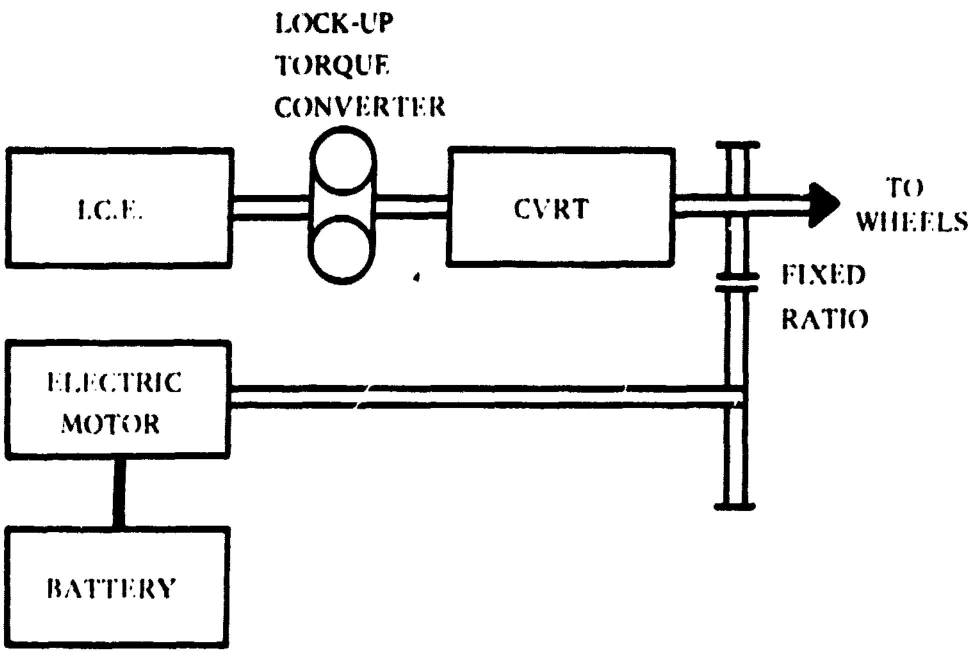


FIG. 3.2-1A – HYBRID VEHICLE: PARALLEL CONFIGURATION No. 3

TABLE 3.2-1

BASIC CHARACTERISTICS OF THE 138 (1100) EUROPEAN ENGINE [1]

ITEM	VALUE
NUMBER OF CYLINDERS	4 in line
BORE, mm	80
STROKE, mm	55.5
TOTAL DISPLACEMENT, cm^3	1116
COMPRESSION RATIO	9.2:1
MAXIMUM POWER AT 5800 R.P.M., HP - kW	60 - 44.1
MAXIMUM TORQUE AT 3500 R.P.M., km	8.3
TOTAL WEIGHT, kg	118

(1) ENGINE TYPE : FOUR-STROKE S.I. ENGINE

3.2.3 The Power Conditioner

The power conditioner of the DC electric motor, schematically represented in Fig. 3.2-2, is based on a transistorised double chopper power unit for motor armature and field current control.

The armature current is limited by the armature chopper until the basic speed of the motor is reached. Then the armature chopper is bypassed and the motor current is limited by excitation field control. When braking occurs the field is reversed and the braking current is controlled by the field control chopper, until the basic speed of the motor is reached. Below the basic speed of the motor the braking (recharge) current is regulated by the armature chopper which acts as a voltage booster.

This feature not only allows regenerative braking down to zero speed but also enables the chopper power unit to be used to charge the battery from a rectified current source.

3.2.4 The Transmission Group

The CVRT transmits power from the ICE main shaft to a shaft coupled to the DC electric motor with a 1 : 1 ratio, through a metallic belt whose max/min rotation speed ratio is 4.12 (maximum ratio = 2.389; minimum ratio = 0.58). The CVRT is shown schematically in Fig. 3.2-3.

The ICE is coupled with the CVRT driving pulley through a torque converter and lock up clutch followed by an inverter group. The driven pulley and the electric motor are coupled with the differential respectively through the ICE clutch and the electric motor clutch, via the drive wheel clutch.

The clutches and the reversing group are driven by on/off electrovalves while belt tension and transmission ratio are determined by means of proportional solenoid operated valves.

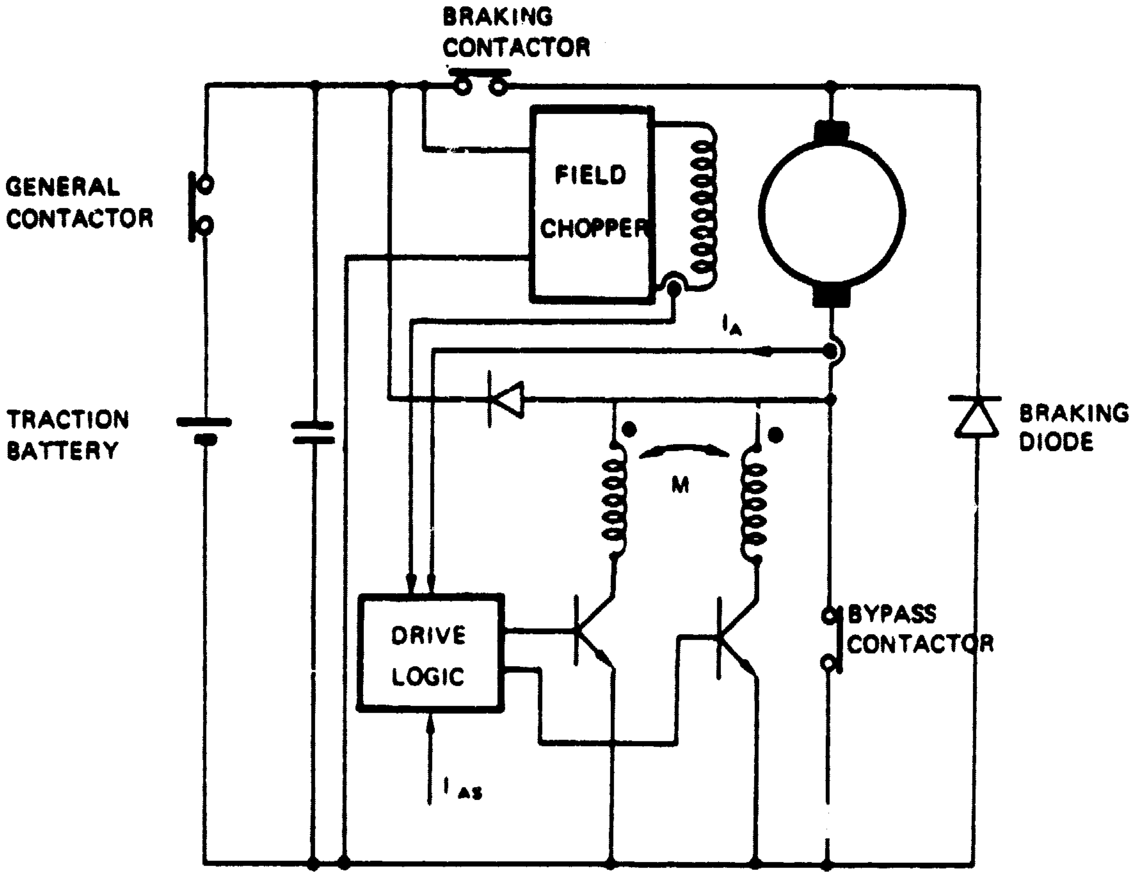


FIG. 3.2-2 – POWER CONDITIONER CIRCUIT DIAGRAM

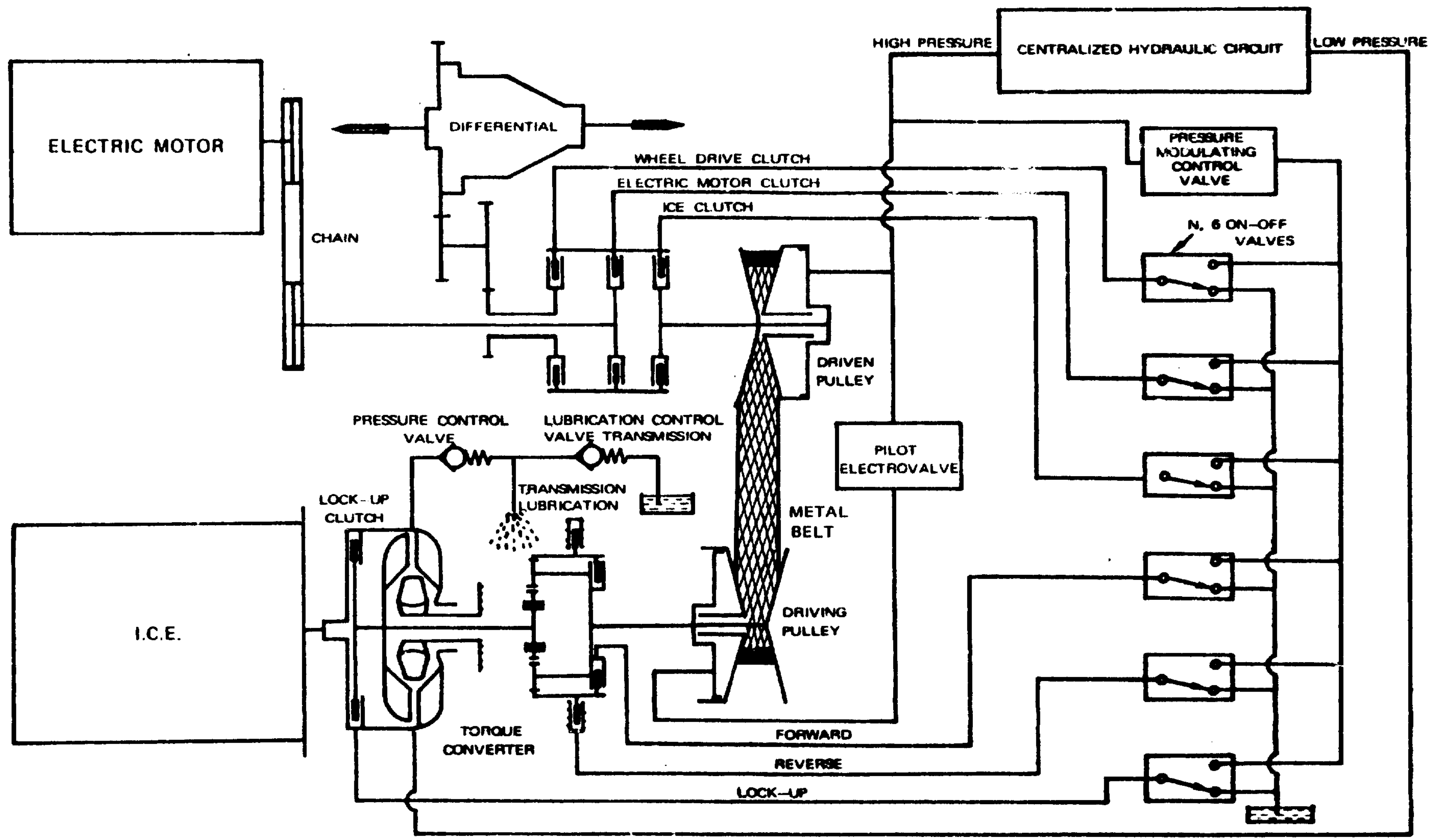


FIG. 3.2-3 – TRANSMISSION DIAGRAM

3.3 THE Ni-Zn BATTERY

The Ni-Zn Battery is based on the Gould 225/HP/HP (225 Ah/High Power/High Profile). The cell developed by Gould particularly suitable for hybrid vehicle operation whereby:

- 225 Ah is the name plate capacity
- High Power definition is to distinguish this line of product from the Medium Power and Low Power batteries developed by Gould for more immediate marketing at lower prices
- High Profile is to distinguish the shape of this battery from that of other batteries built in lower hight ("galf cart" and "starter" sizes).

The cell which is characterized by a weight of 5.3 kg, a height of 39.5 cm, a width of 18 cm and a thickness of 4.5 cm. The cell itself is provided with ribs and grooves such that when the cells are pressed together they remain interlocked with each other, leaving 5 cm channels for cooling air flow. Groups of 5 cells, secured toghether with metal plates, form the modules (shown in Fig. 3.3-1) which are used to build the battery.

The battery is formed by 12 modules, weighs approximately 320 kg and is enclosed in a sealed plastic container with external dimensions of 100 cm x 41 cm x 60 cm. The battery main characteristics are given in Table 3.3-1. With reference to the items shown there the following comments should be taken into account:

- Stored Energy is the energy deliverable by the battery when completely discharged from a fully charged condition (100% DOD)
- Usable Energy is the energy that can be used on every discharge cycle, corresponding to a depth of discharge (DOD) level of 80%. This value of DOD, which the battery discharge life refer to, avoids deep discharges which would curtail the battery lifetine and therefore jeopardize an economical utilization of the vehicle
- Price for rifeneration is the price to be paid for a new battery when returning battery of the same size used until the end of its lifetime.

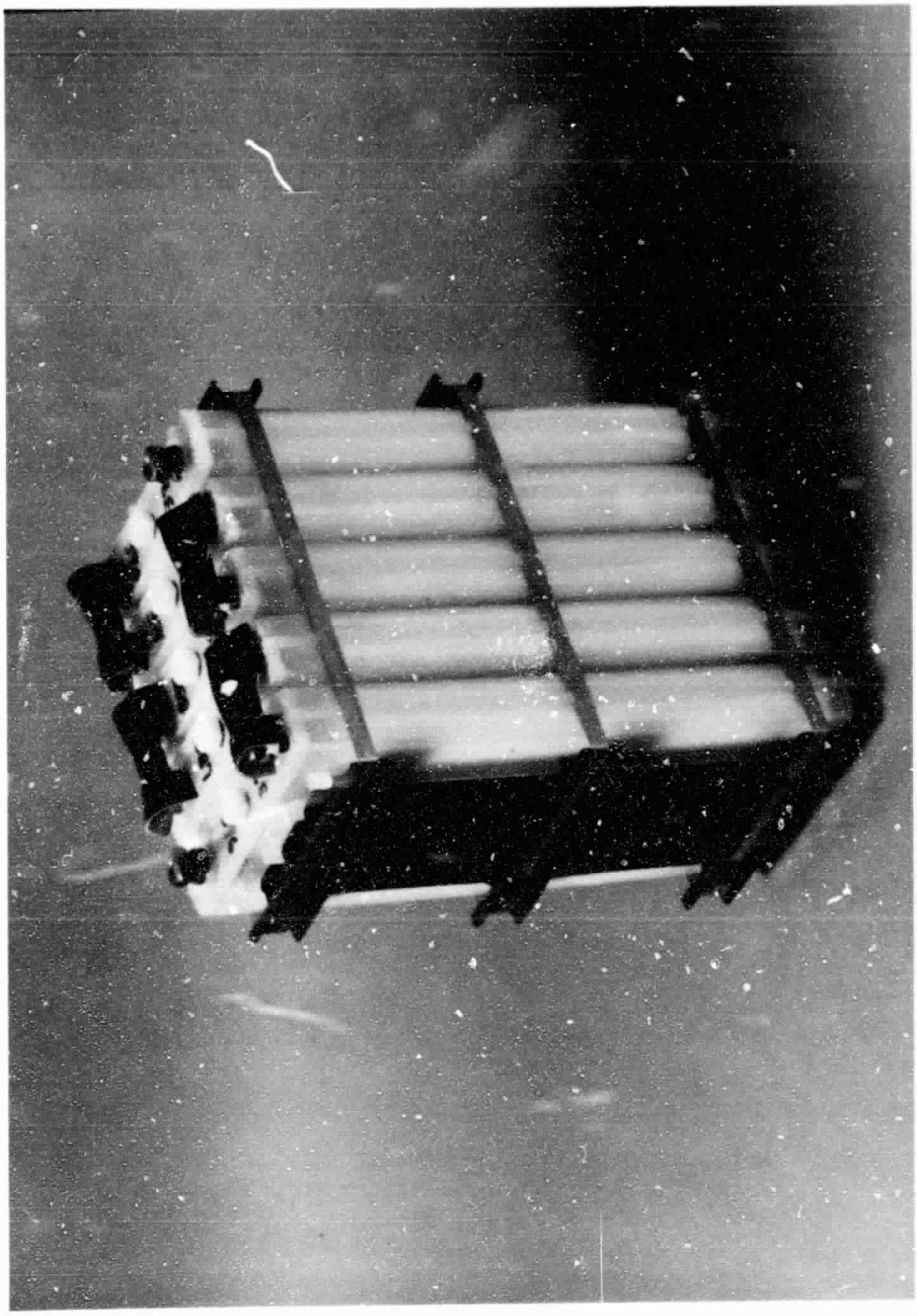


FIG. 3.3-1 — Ni-Zn BATTERY MODULE (FIVE 225/IIP/IIP CELLS)

TABLE 3.3-1

BATTERY CHARACTERISTICS

ITEM	BATTERY TYPE
	Ni - Zn
STORED ENERGY, kWh	22
USEABLE ENERGY, kWh	17.5
NOMINAL VOLTAGE, V	96
MAX VOLTAGE ON CHARGE, V	120
MIN DISCHARGE VOLTAGE, V	84
MAX DELIVERABLE POWER FOR 15s, kW	45
POWER DELIVERABLE FOR 15min., kW	40
POWER DELIVERABLE FOR 30min., kW	30
PRICE, $/kWh	75 (1)
LIFE CYCLES (80% DEPTH OF DISCHARGE)	400
LIFE CYCLES (40% DEPTH OF DISCHARGE)	1600

(1) PRICE FOR REGENERATION

It should be noted that the power deliverable by the battery in dynamic conditions, even at 80% (DOD) exceeds by a significant margin the power required at any time by the electric propulsion system, as discussed in the following Subsection 4.3.

The battery is cooled by an electric fan whenever an excessive temperature is reached and is equipped with temperature, voltage and current sensors which provide the basic information used for battery monitoring, protection and optimal control.

The battery is equipped with a centralized topping-up system which also serves to vent gases generated at the end of charge or by cell reversal. These are safely conveyed out of the vehicle through a flame braker and a one way valve which prevents backstreaming of CO_2 with consequent carbonation of the alkaline electrolyte.

Availability of 225/HP/HP cells from the Gould pilot plant for the hybrid vehicle program as well as for demonstration programs is guaranteed, while scaling up of the manufacturing capability only awaits maturing of the electric vehicle market.

3.4 MECHANICS AND TIRES

3.4.1 Mechanics

As already mentioned in the general description, vehicle mechanics are characterized by a Mc Pherson type front wheel suspension, a torsion bar rear suspension, power assisted disk brakes and a rack and pinion driving system suitable for closed circuit power assistance.

All mechanical parts can be supplied from the standard Fiat stock and adapted for the hybrid vehicle by minor modification to match the different design trim.

3.4.2 Tires

The vehicle proposed is designed to use low rolling resistance tires. The success obtained by Pirelli during preliminary demonstration shows that only a limited effort will be needed to design and manufacture the prototypes to suit the proposed hybrid vehicle requirements. Commercial availability of low-friction tires is likely expected, given the importance of lowering the road load power demanded and the degree of technological development related to low rolling resistance tires.

3.5 THE BODY

The self bearing body preliminary design was developed to meet the following goals:

- low drag coefficient (0.30)
- light weight
- satisfactory crash resistance.

The external appearance of the vehicle body is shown in Fig. 3.5-1, 3.5-2 and 3.5-3 while a schematic representation of its construction is given by the sketch in Fig. 3.5-4.

The steel frame structure is based on that of the LANCIA GAMMA SEDAN, modified in order to allow battery installation, enlarged to meet increased roominess requirements and reinforced by a new longitudinal member to bear the increased thrust produced by the presence of the battery in the event of frontal crash.

The steel frame is integrated with glass fiber reinforced plastic panels which in the above sketch are shown separately from the frame.

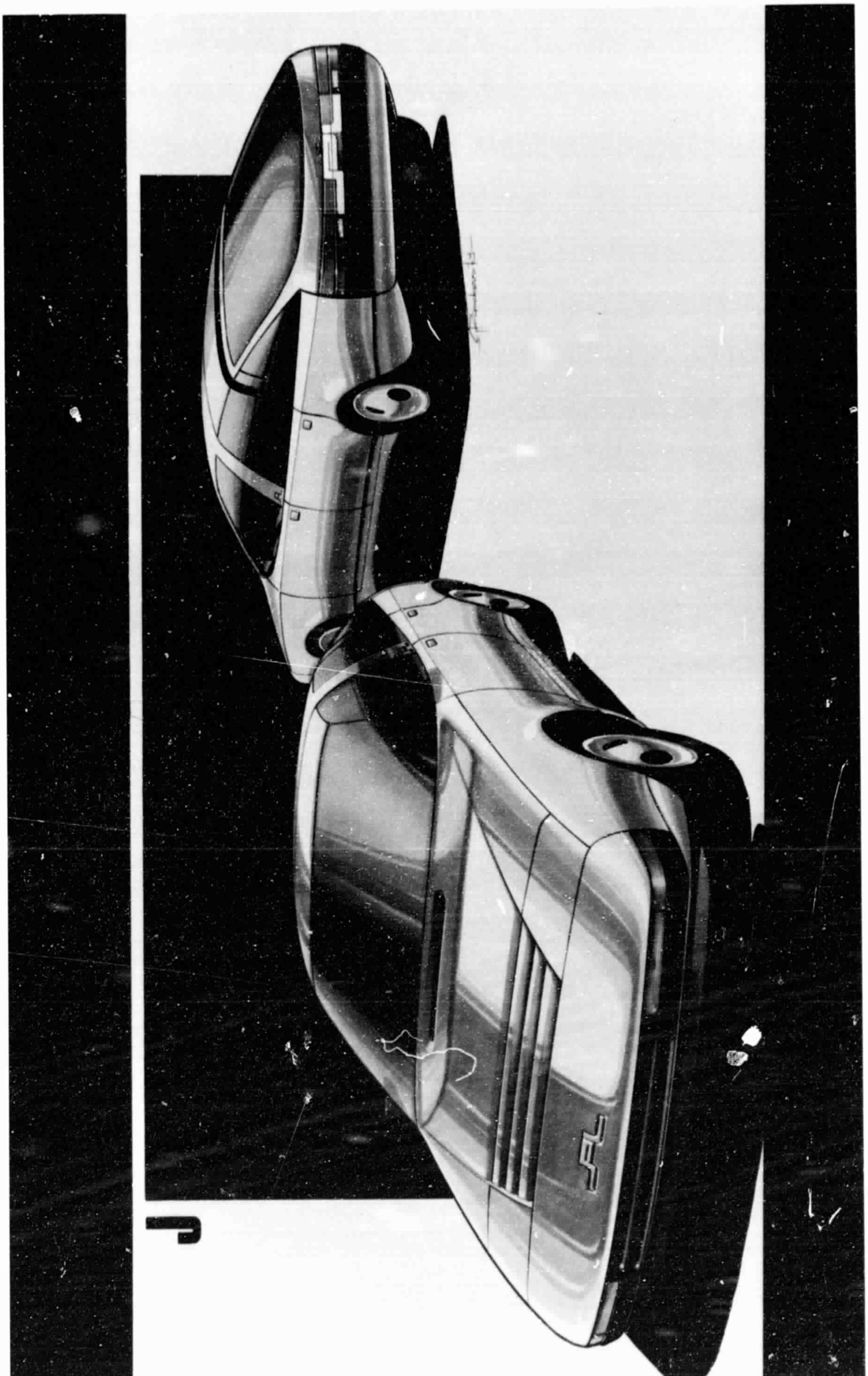


FIG. 3.5-1 — BODY SHAPE — THREE QUARTER FRONT AND REAR VIEWS

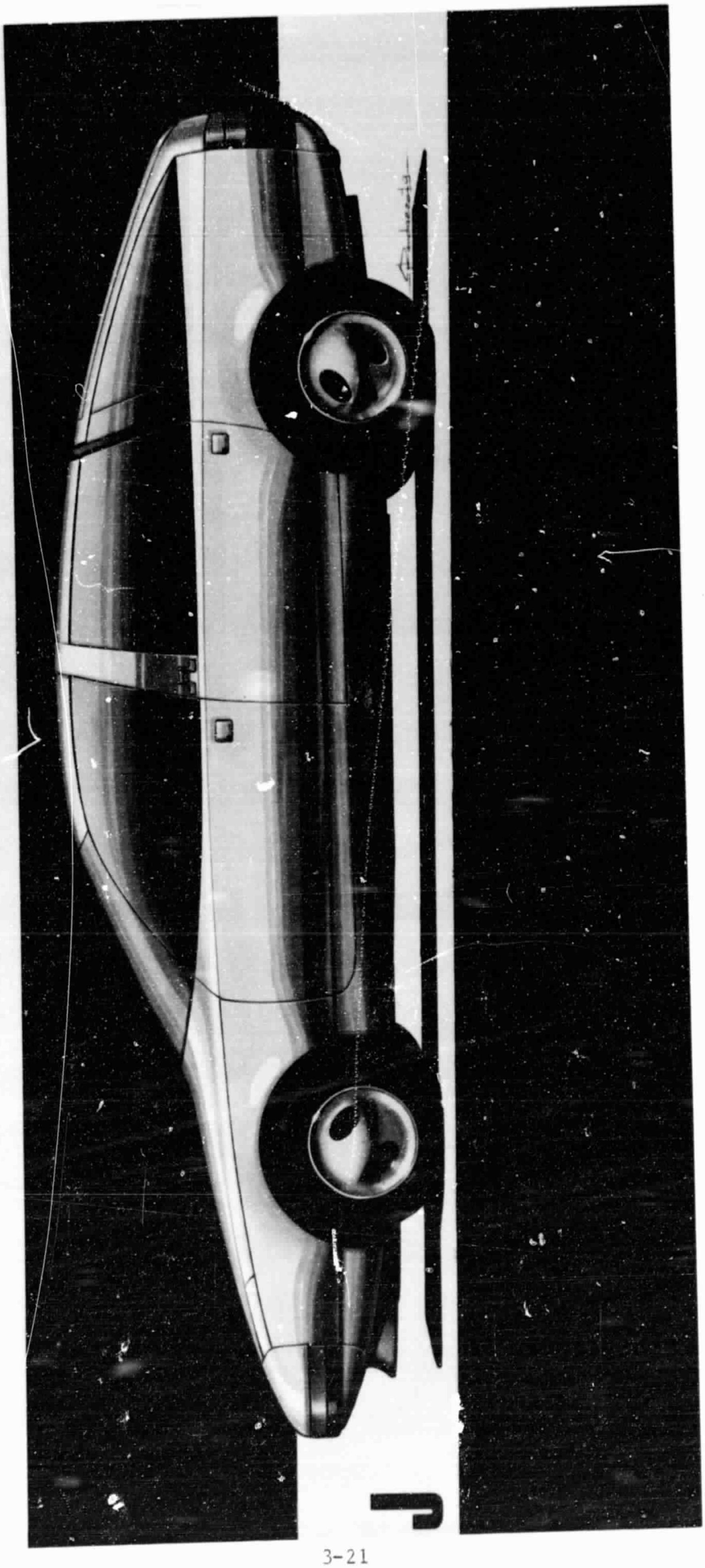


FIG. 3.5-2 — BODY SHAPE — SIDE VIEW

FIG. 3.5-3 -- BODY SHAPE — FRONT AND REAR VIEWS

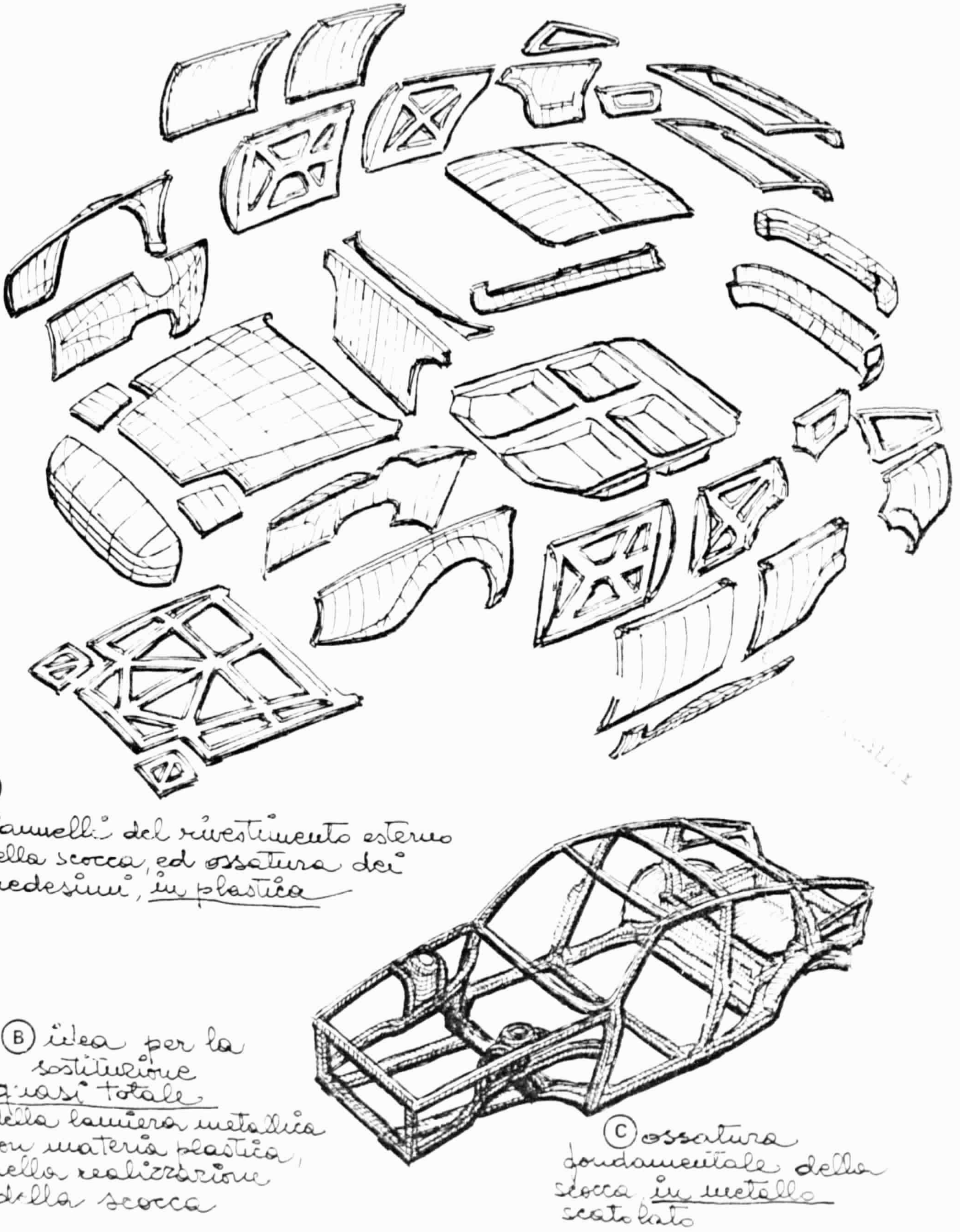


FIG. 3.5-4 – ORIGINAL SKETCH OF BODY STRUCTURE STUDY

LEGEND FOR PAGE 3-23 CALL OUTS

A – Outer body plastic panels and corresponding structure.

B – Schematic study for an almost total replacement of metal sheets with plastic material for autobody implementation.

C – Basic structure of the body in boxed metal.

FIG. 3.5-4 – ORIGINAL SKETCH OF BODY STRUCTURE STUDY

3.6 THE ON BOARD COMPUTER (OBC) CONTROL SYSTEM

The OBC hardware considered is derived, with minor architectural modifications, from that developed by C.R. FIAT for the "132 electronic vehicle program". This is a multiprocessor system based on the INTEL 8085 CPU and includes:

- Programmable Peripherals
- RAM and EPROM as required to store all control programs and volatile variables
- Operative system that provides for parallel processing and man-machine interactions.

The OBC control software is organized on two hierarchical levels, as schematically shown in Fig. 3.6-1.

- The strategic decision level, which:
  - . selects operation mode (electric-only, hybrid, emergency thermal-only) according to driver instructions
  - . performs battery management and other monitoring and protection functions
  - . in hybrid operation defines, in real time, optimal power sharing between ICE and electric motor.
- The actuation level and subsystem control, which drives:
  - . the ICE throttle position
  - . the electric motor via the power conditioner
  - . the CVRT.

In conclusion the various strategies for control of the propulsion system to be implemented by the OBC control system can be summarized and described with reference to the complete set of available operating conditions:

a) Electric-only (engine turned-off) with reduced performance

b) Hybrid with electric primary and full performance

c) Intermediate hybrid with full performance

d) Hybrid with thermal primary and full performance

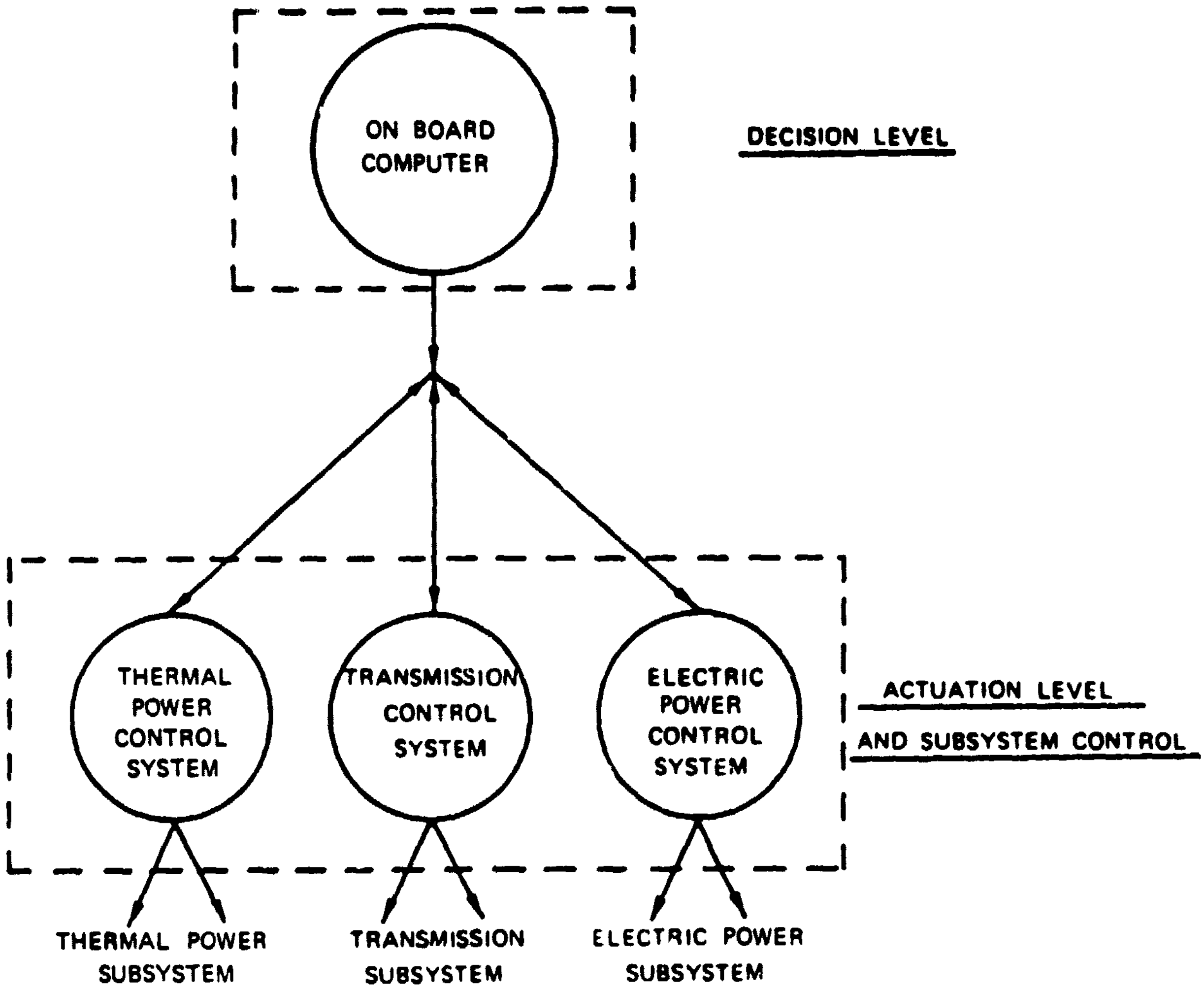


FIG. 3.6-1 – ON-BOARD COMPUTER HIERARCHY LEVELS

e) Thermal-only (electr. motor disenergized) with reduced performance.

If the reduced performance of the electric only mode is adeguate to satisfy the required acceleration and/or grade conditions (as for the standard Federal Driving Cycles) maximum fuel economy can be obtained by keeping the engine turned-off until the battery reaches the maximum operating DOD (80%).

The system would then go automatically to the d) mode.

If full performance is desired and the expected driving range and mode are such that maximum operating DOD cannot be reached before next recharge opportunity the control system would try to use as much electric energy as possible and operate the vehicle in the b) mode (accent on fuel saving rather than on battery life: maximum fuel economy with full performance minimum range).

If full performance is required but the expected driving range and mode are such as to exceed max operating DOD, to assure full performance over the entire range the control system would operate the vehicle at a predetermined value which would allow to reach said DOD at the expected range end, mode c), decreasing fuel economy with increasing range.

If the maximum operating DOD is reached the control system would operate the vehicle in the d) mode. The same operating mode can be conceived to be imposed by a driver willing to stress the battery life extension rather than the maximum fuel economy at DOD levels lower than said maximum (no battery discharge, infinite range with refueling, minimum fuel economy).

In case of electric motor or battery out-of-service the vehicle can be operated (with reduced performance) as a conventional vehicle using thermal power only (emergency conditions).

SECTION 4

ALTERNATIVE HYBRID VEHICLE DESIGN

OPTION AND RATIONALE OF THE ADOPTED SOLUTION

Once the size and type of vehicle was defined, general guidelines were set by C.R. FIAT, to be used for the selection of the hybrid propulsion system configuration, the key vehicle components and the control strategy.

On the one hand, the vehicle performance would be such as to meet Performance Specifications and JPL Minimum Requirements, while gaining wide public acceptability in competition with 1985 conventional vehicles. The required performance is achievable by a vehicle characterized by:

- low weight
- low drag coefficient
- low rolling resistance tires
- high efficiency propulsion system.

On the other hand, design implementation cost and development risks would be minimized by using, when applicable, reliable and readily available solutions.

Finally, impact on projected vehicle cost would also be considered in selecting design alternatives.

4.1 HYBRID POWER TRAIN CONFIGURATION ALTERNATIVES

4.1.1 Parallel vs. Series Hybrid Configuration

The series hybrid configuration was excluded from the beginning of the project as the mission for which the vehicle was designed includes highway trips, where the ICE provides most of the power. In such missions a series configuration would result in an unnecessary loss of power trasmission efficiency. A series configuration would furthermore demand an electric motor-power conditioner system able to supply by itself all the power needed to satisfy the performance requirements, which would therefore be heavy and bulky.

4.1.2 With vs. without CVRT

The solution with CVRT was selected to avoid use of the ICE in the low efficiency and/or high emission regions. The use of the CVRT also allows thermal-only traction in an emergency, which would not be possible with an ICE directly coupled to the trasmission chain.

4.1.3 With CVRT on ICE only vs. CVRT on the Whole Propulsion System

The solution with CVRT on the ICE only was selected to permit direct coupling of the electric motor to the trasmission chain, thus minimising trasmission inefficiency on a vehicle which is designed for frequent driving with electric-only traction. Furthermore, a CVRT for use on the whole propulsion system would have to be rated for a 71 kW rather than 45 kW propulsion group with consequent increase in bulk, weight and inefficiency during low power driving.

4.1.4 Front or Rear Positioned, Front or Rear Wheel Drive, Longitudinally or Trasversally Mounted

The decision to propose a front wheel drive vehicle with the propulsion system mounted trasversally between the front wheels was taken because FIAT experience shows that this solution allows the best utilization of the volume allocated to the propulsion system, allowing at the same time good access for maintenance. Tilting the ICE by 20° allows the front profile of the vehicle to be kept low, thereby improving its aerodynamic characteristics.

4.2 CONTROL STRATEGY ALTERNATIVES

4.2.1 On/off vs. Continuous ICE Power Contribuition

Among the hybrid power system control strategy options, consideration was given to the on/off solution; this consists of using the ICE to power the traction train and recharge the battery whenever the latter reaches a given discharge state, returning to electric-only traction as soon as the battery is sufficiently recharged. The main advantage of this control strategy is the possibility of using the ICE in optimum operating conditions (high load, independently of the requirements of the power train).

However, the above solution was excluded because:

- the electric energy used for traction would be derived from the ICE through the following inefficient conversion chain: mechanical to electrical, electrical to electrochemical, electrochemical to electrical, electrical to mechanical
- use of the ICE in the high efficiency region is also possible with other control strategies.

4.2.2 Continuous Hybrid vs Electric-Only Followed by Hybrid Operation Mode

In the continuous hybrid operation mode only an appropriate fraction of the total power required at the vehicle wheels is obtained from the thermal engine.

Being P_{th} the thermal power contribution and P_{tot} the total power required at wheels, if a coefficient α is defined as:

$$\alpha = \frac{P_{th}}{P_{tot}}$$

the electric power contribution can be espressed as

$$P_e = P_{tot} (1 - \alpha)$$

In the normal hybrid operation mode the automatically or manually preset value of α will be mantained as long as compatible with the total power required by actual driving conditions and the maximum available electric and thermal power.

When, depending on the value actually imposed, the electric or thermal power is saturated, the actual power requirements will be automatically met using the remaining available power source. The vehicle driver can either set at the beginning of operation the range he proposes to cover, letting the control system define subsequently, or set manually to any value from 0 (electric-only traction) to ~ 1 (hybrid traction without battery discharge).

The alternative operation mode consists of driving with electric only traction ($\alpha = 0$) up to a preset discharge state of the battery and then starting the ICE and driving with $\alpha \simeq 1$ using the electric power system only to store energy during regenerative braking and supply propulsion peak power when the instant power demanded by the driver exceeds that available from the ICE.

The second alternative is preferred as it permits better fuel and energy economy by never using the ICE in the low load conditions typical of lower values of α . It is however applicable only if the performance requirements of the mission can

be met by electric-only traction, as in the case of Federal Urban and Highway Driving Cycles (FUDC, FHDC).

4.3 BATTERY ALTERNATIVES

The conclusion reached by C.R. FIAT, after evaluating all considerations related to the ability of the hybrid vehicle to meet its performance, cost and petrol and energy saving goals, is that the battery should not weigh more than 20% of the overall vehicle curb weight; in this case 300-320 Kg. Analyses carried out a posteriori showed that this conclusion, for different reasons, roughly applies to all types of batteries considered.

Three types of batteries were compared, the final selection being made only after calculation of optimised vehicle performance for each type:

- the improved Lead-Acid battery
- the high power type Ni-Zn battery
- the high temperature Na-S battery.

The sketches of general layout and key features for each type of battery suitable for the proposed vehicle are given in Fig.4.3-1, 4.3-2 and 4.3-3.

A summary of battery characteristics as used in the alternative vehicle propulsion systems that have been compared is provided on Table 4.3-1.

The maximum power refers to the on-the-vehicle operating conditions, that is to the maximum power actually deliverable to the electric motor used for a given alternative with the corresponding battery;

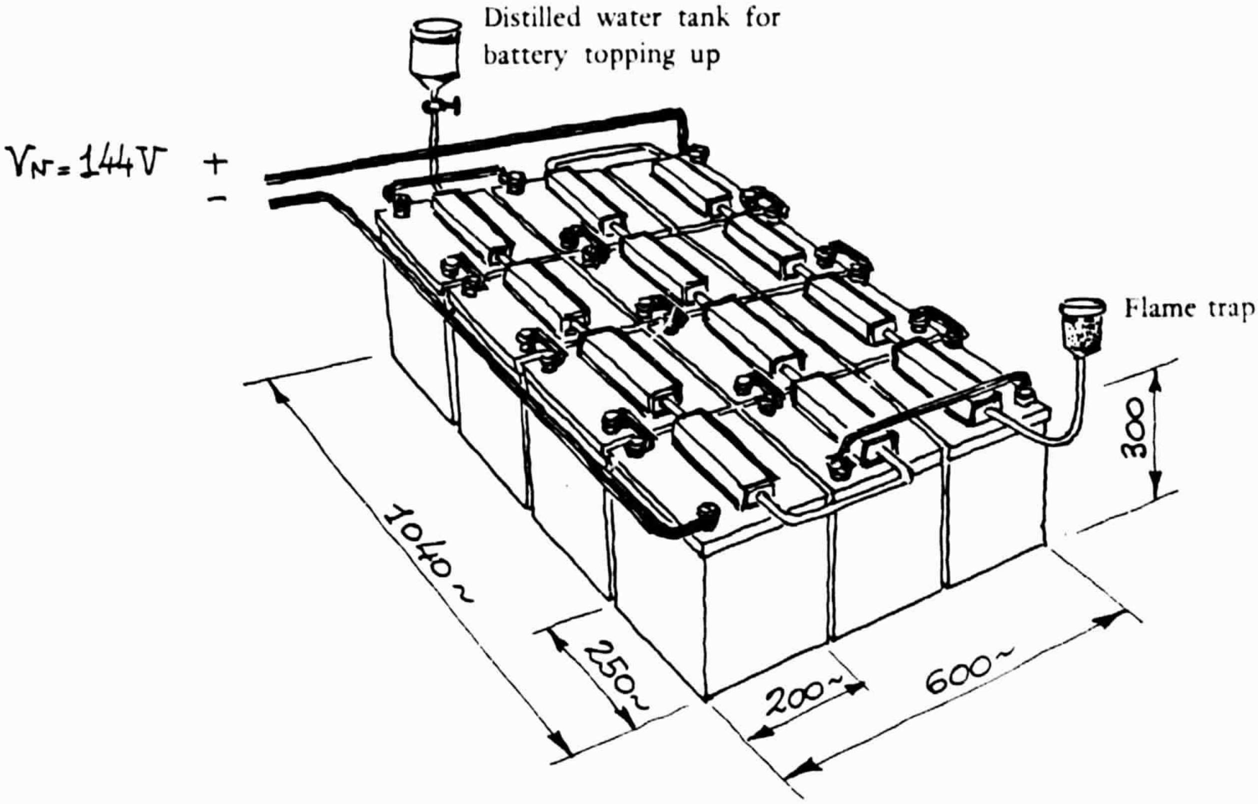
The values thereby shown have been provided by

Brown Boveri (Na-S batteries)

Gould (Ni-Zn batteries)

Magneti Marelli (Lead-Acid battery).

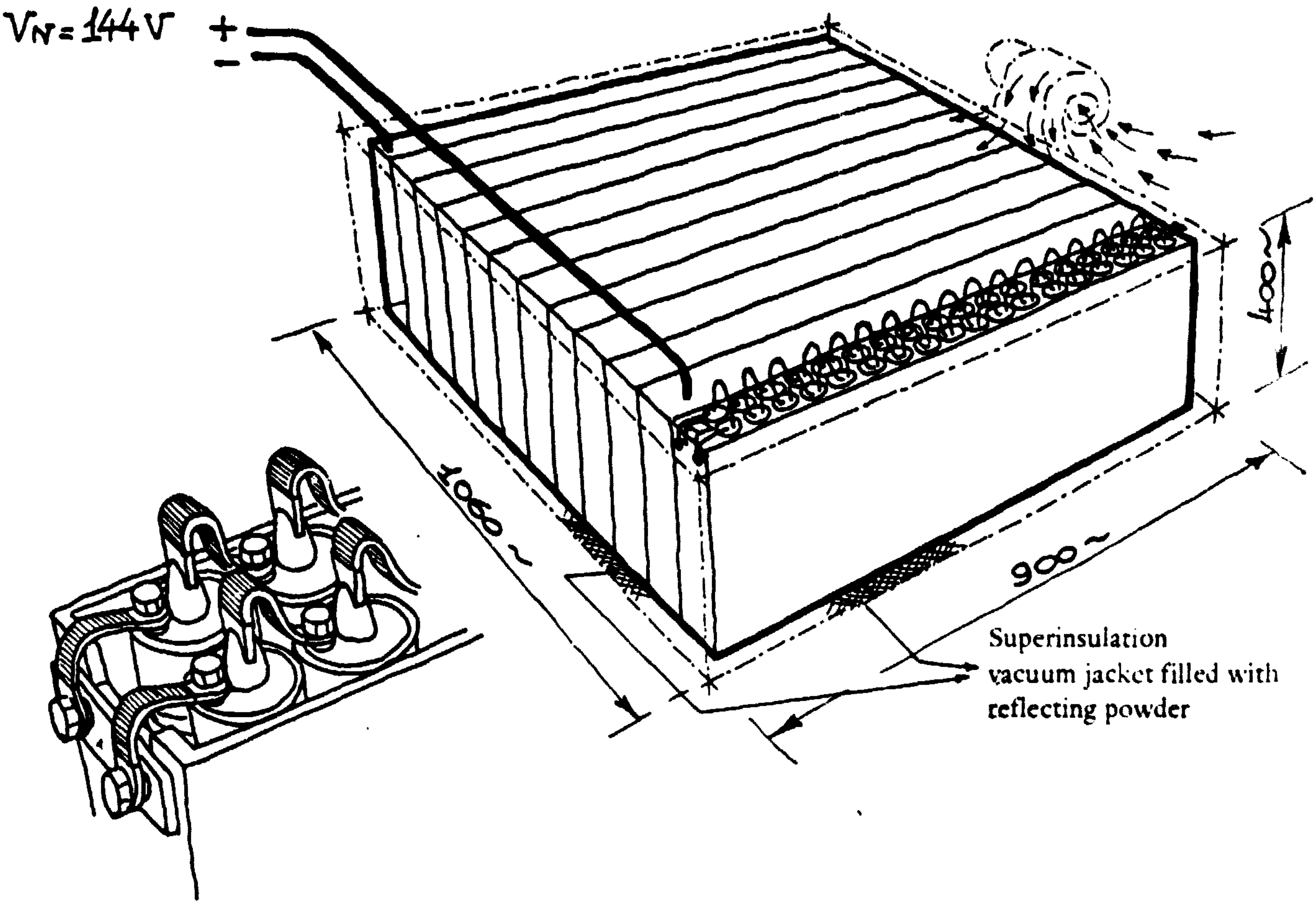
The Lead-Acid battery was eliminated because the tests carried out by Marelli, and even the most optimistic development



Weight Kg 300
Low stored energy
Low power availability
Reduced volume
Commercially available
Sufficient cycle life
Low price

Cannot satisfy at the same time requirements of
- Power availability for electric only traction
- Use of a relevant share of electric primary electrical energy

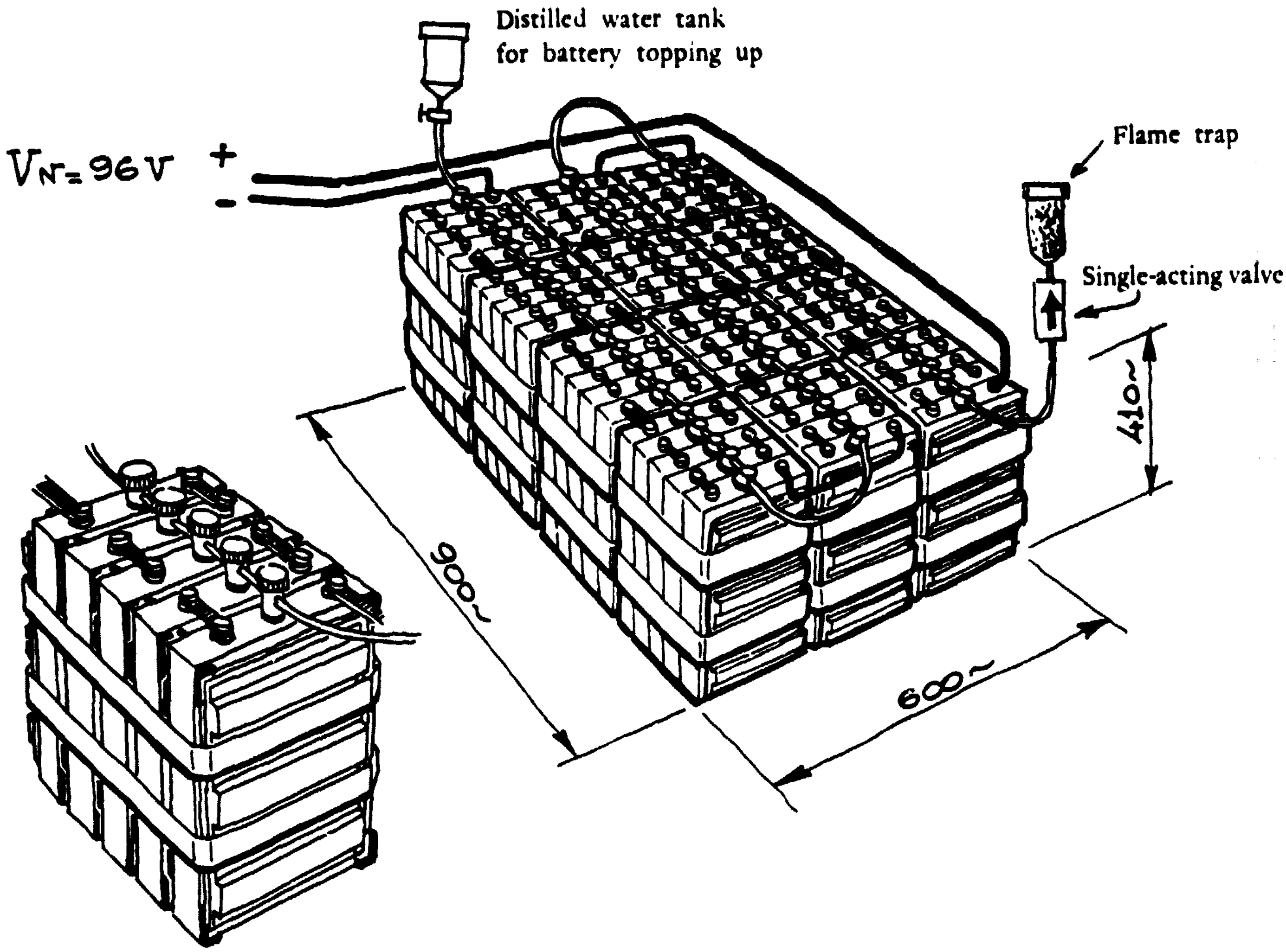
FIG. 4.3-1 – SKETCH OF LEAD-ACID BATTERY LAYOUT



Weight Kg 320
High stored energy
Medium power availability
Large volume
High operating temperature (350° C)
Extended cycle life
High price

Not available in the very near term
Does not satisfy the power requirement for
electric-only traction

FIG. 4.3-2 – SKETCH OF SODIUM-SULPHUR BATTERY LAYOUT



Weight Kg 320
Good energy content
High available power
Medium volume
Technically available
Cycle life comparable with Lead-Acid type
Medium price

Available in very near term
Supplies power in excess of that required
for electric-only traction

FIG. 4.3-3 – SKETCH OF NICKEL-ZINC BATTERY LAYOUT

TABLE 4.3-1

BATTERY CHARACTERISTICS

ITEM	BATTERY TYPE		
	Na - S	Lead - Acid	Ni - Zn
STORED ENERGY, kWh	45	14.4	22
USEABLE ENERGY, kWh	36	7 - 11	17.5
NOMINAL VOLTAGE, V	144	144	96
MAX VOLTAGE ON CHARGE, V	–	190	120
MIN DISCHARGED VOLTAGE, V	–	110	84
MAX DELIVERABLE POWER FOR 15s, kW	32 (1)	30	45
POWER DELIVERABLE FOR 15min., kW	–	–	40
POWER DELIVERABLE FOR 30min., kW	–	–	30
PRICE, $/kWh	70 - 100 (2)	70 - 80 (2)	75 (3)
LIFE, 80% DEEP OF DISCHARGE, CYCLES	600	400 - 800	400
LIFE, 40% DEEP OF DISCHARGE, CYCLES	1200	1000 - 2000	1600

(1) IN Na - S BATTERY MAX. POWER IS NOT RELATED TO TIME.

(2) PURCHASE COST.

(3) PRICE FOR REGENERATION

predictions, indicate that neither today nor by 1985 will it be able to deliver the power needed to perform the standard cycles (FUDC and FHDC) in electric only traction, or to deliver the amount of electric energy needed for a substantial petrol saving in the typical mission identified by C.R. FIAT for the hybrid vehicle proposed.

The Sodium-Sulphur battery was not adopted because it is not able, within the specified size limitations, to deliver the electric power needed to perform the standard cycles in electric-only traction. A Na-S battery of bigger size could be used, to meet electric-only traction requirements, but its cost would only be recovered by those users who cover extremely long daily ranges and so take full advantage of the electrochemically stored energy. In any case the cells selected for this project would not have been available in a sufficiently industrialized version within the Phase II time schedule.

The Nickel-Zinc battery was selected because it can deliver, for any allowed discharged state (max 80%) and condition, an electric power in excess of that needed for electric-only traction on Federal standard cycles. In fact at 80% DOD the Ni-Zn battery adopted would shill be able to deliver over 40 kW for 15'. The motor, on the other hand can only absorb at recurrent times an electric power of 39 kW max, for few seconds only when the vehicle is driven on grades at speeds 35 and 50 kw/h. This condition is, in any event, very severe for the motor itself which is protected against overheating and can only supply continuously no more than 20 kW.

The motor can however supply 35 kW for a maximum duration of 30 s and 30 kW for about 60 s. This feature of high power availability allows:

- electric only traction for ranges lower than 130 km with consequent infinite fuel economy
- electric only traction down to a set value of depth of discharge (DOD) followed by hybrid operation for longer ranges.

The last operating mode described is the cornerstone of the

control strategy selected which, as already pointed out, permits maximum fuel and energy economy. Fig.4.3-4 shows the fuel economies achievable with optimised hybrid vehicles powered by Lead-Acid, Ni-Zn and Na-S batteries respectively. The Ni-Zn battery powered vehicle is assumed to be driven in electric-only mode until 80% DOD and then in hybrid mode with no average change in battery discharge state. The other vehicles operate with a share between thermal and electric power, kept to a constant mean during the mission. The value is determined for short ranges by the total drive power requirement (not fulfillable by the electric propulsion system), and for longer ranges by the necessary share between electrochemically stored energy and energy stored as fuel.

4.4 ELECTRIC MOTOR AND POWER CONDITIONER ALTERNATIVES

4.4.1 Commutatorless Motor vs. Conventional Motor

The theoretical advantages of the commutatorless motor are well known and can be summarized as follows:

- smaller volume
- lower weight
- elimination of the wear factor introduced by the mechanical commutator
- use of readily available, low power transistors.

A commutatorless motor of medium power is under development at the C.R FIAT. However, due to the tight schedule of Phase II of the program, adoption of the commutatorless motor would demand high design implementation costs and some development risk. A traditional DC electric motor, derived from an existing FIAT model whose manufacturability and ruggedness are amply demonstrated, was therefore selected.

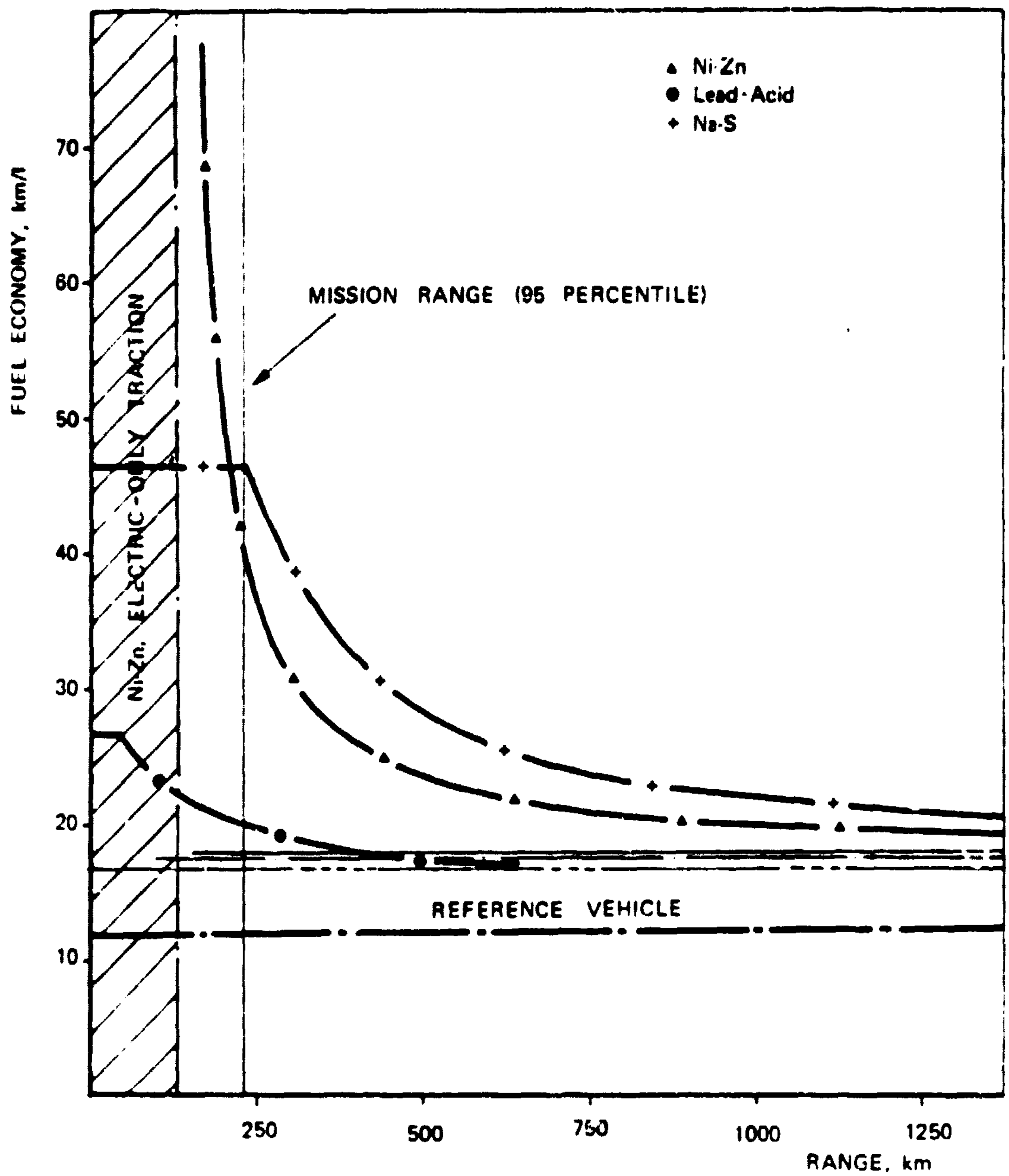


FIG. 4.3-4 — FUEL ECONOMY VS. RANGE

4.4.2 Thyristor vs. Transistor-based Power Conditioner

The inherent advantages of a transistor-based power conditioner result from the higher working frequency which allows a very low ripple even without armature smoothing inductance. As a consequence the ohmic losses are reduced, efficiency is increased and the overall weight is also reduced. An additional advantage of high frequency operation is the reduction of acustic noise.

The relatively low battery voltage (V_N = 96 V), and the experience gained in electric vehicle power conditioning allows C.R. FIAT to define the transistorized power conditioner as a low risk item in all respects, which does not demand a major design implementation effort.

4.5 INTERNAL COMBUSTION ENGINE ALTERNATIVES

4.5.1 Diesel vs. Spark Ignition Engine

The Diesel engine is known to be more efficient than the spark ignition one. The efficiency gap is considerable under low load operating conditions but is less important with a high load. The choice of a control strategy which demands of the ICE either no power at all, or most of the power needed by the vehicle through a CVRT, reduces the efficiency gap between diesel and spark ignition engines to a minimum, as high load conditions mostly apply.

The drawbacks of the diesel engine are:

- higher weight and volume
- lower availability
- higher cost
- higher NO_x emission

Consequently, the spark ignition engine was selected for this project.

4.5.2 Electronic Controlled Injection vs Feed-Back Carburetor

The advantage of the electronic controlled injection system is mainly confined to increased efficiency and minimized emissions, particularly when the engine operates in extreme conditions.

The control strategy selected and the use of the CVRT make the conventional solution (feed-back carburator) competitive in performance with the more sophisticated one (electronic controlled injection). The conventional solution implying no design implementation cost and no development risk was therefore chosen.

4.6 ON BOARD COMPUTER COMPONENT ALTERNATIVES

Since the "132 electronic vehicle" program was completed new microprocessor system components have become commercially available. The evolution in this field is so rapid, however, that we are convinced that 1985 systems wiell include components different from those to be adopted for the Hybrid Vehicle prototype(s) development. It was therefore proposed to use wherever possible techniques and components which are currently available and well known to C.R. FIAT.

4.7 BODY MATERIAL ALTERNATIVES

Three basic alternatives were possible for implementation of the vehicle self-bearing body:

- all metallic body structure
- all plastic body structure
- metal frame/plastic panel integrated body structure.

The first solution was not adopted since it results in a conventional, heavy body not adequate to meet the overall vehicle weight goals. The second solution was not adopted because it

demands a high implementation design cost, particularly with regard to safety and crashworthiness considerations.

The third solution was chosen as a good compromise between the first two as it allows acceptable weight goals to be met with a minimum development risk and use of metal parts from body section of vehicles within the FIAT fleet.

P A R T I I

SPECIFIC TOPICS

RELATED TO THE PERFORMED PROGRAM

S E C T I O N   5

CONTRACT ACTIVITIES NOT COVERED BY

THE ISSUED TASK REPORTS

5.1 IDENTIFICATION OF "REFERENCE VEHICLE TECHNOLOGIES"

During the "Mission Analysis and Performance Specification Studies" the fuel economy characteristics of the Candidate Reference Vehicle were defined using the 1985 projections supplied by the JPL GUIDELINES, the car manufacturer's projections obtained from the specialized press (Automotive News) and other projections presented in the "Rulemaking Support Paper Concerning the 1981 to 1984 Passenger Auto Average Fuel Economy Standards".

This section provides a summary of vehicle characteristics, related to fuel economy, obtainable by means of improvements on the various design parameters of conventional large size 1978 passenger vehicles.

This study was intended to validate the assumption made during Phase I program, which states:

"To meet the 1985 fuel economy requirements with the projected new car fleet mix, the large size 1985 vehicle shall incorporate all the available advanced design concepts contributing to the improvement of fuel economy characteristics".

In this analysis any consequential effect on engine emission which could require fuel consumption corrections has been neglected.

Consumption figures relative to the 1978 six-cylinder Chevrolet Impala and reduction in fuel consumption due to improvements of the various design parameters have been calculated by means of the "SPEC '78" Computer Simulation Program. This program was also used to evaluate the hybrid vehicle performance characteristics.

The data thus obtained are given in Table 5.1-1, which permits comparison of the various configurations in analytical terms. Table 5.1-1 should be read in conjunction with Fig. 5.1-1, which shows achievable improvements in fuel economy in comparative terms for the various cycles. It should be pointed out that the vehicle used for the evaluation of technological improvement levels is not the A* reference vehicle (1978 Chevrolet Impala) but

TABLE 5.1-1 – FUEL ECONOMY OF VARIOUS CONVENTIONAL VEHICLE CONFIGURATIONS

PARAMETER		A*	A	B			C			D			E(5)			F(5)			G(5)(6)		
		Absol. (1)	Absol.	Absol.	% Over A	–	Absol.	% Over B	% Over A	Absol.	% Over C	% Over A	Absol.	% Over D	% Over A	Absol.	% Over E	% Over A	Absol.	% Over F	% Over A
CURB WEIGHT, kg		--	1644	1453	-11.6	–	1453	–	-11.6	1453	–	-11.6	1453	–	-11.6	1453	–	-11.6	1453	–	-11.6
Cx		–	0.48	0.40	-16.7	–	0.40	–	-16.7	0.30	-25	-37.5	0.30	–	-37.5	0.30	–	-37.5	0.30	–	-37.5
A, m2		–	2.470	2.425	-1.8	–	2.425	–	-1.8	2.425	–	-1.8	2.425	–	-1.8	2.425	–	-1.8	2.425	–	-1.8
Kn		–	1.00 (2)	0.60 (3)	-20.0	–	0.45 (4)	-43.7	-55.0	0.45	–	-55.0	0.45	–	-55.0	0.45	–	-55.0	0.45	–	-55.0
DISPLACEMENT, l		–	4.1	4.1			4.1			4.1			3.0	-26.8	–	3.0	–	-26.8	3.0	–	-26.8
LOCK-UP CLUTCH		–	NO	NO			NO			NO			NO			YES			YES		
ICE FUEL ECONOMY MPG (7)	EPA Composite	18.9	20.3	21.7	+6.9	–	22.8	+5.07	+12.3	23.8	+4.4	+17.2	27.3	+14.7	+34.5	28.1	+2.9	+38.4	33.7	+19.9	+66.0
	FUDC	17.0	18.5	19.4	+4.9	–	20.2	+4.1	+9.2	20.7	+2.5	+11.9	24.4	+17.8	+31.9	25.0	+2.5	+35.1	28.8	+15.2	+55.7
	FHDC	22.0	23.2	25.3	+9.0	–	27.2	+7.5	+17.2	29.4	+8.1	+26.7	32.1	+9.2	+38.4	33.2	+3.4	+43.1	42.5	+28.0	+83.2

(1) REFERENCE VEHICLE: IMPALA '77
(2) CONVENTIONAL TIRES
(3) RADIAL TIRES
(4) LOW ROLLING RESISTANCE TIRES
(5) POWER TRAIN HORSEPOWER AS REQUIRED TO MEET MISSION PERFORMANCE SPECIFICATIONS ON ACCELERATION
(6) CONTINUOUS VARIABLE RATIO TRANSMISSION INSTEAD OF AUTOMATIC TRANSMISSION
(7) FUEL ECONOMY EVALUATED WITH 140 kg TEST PAYLOAD

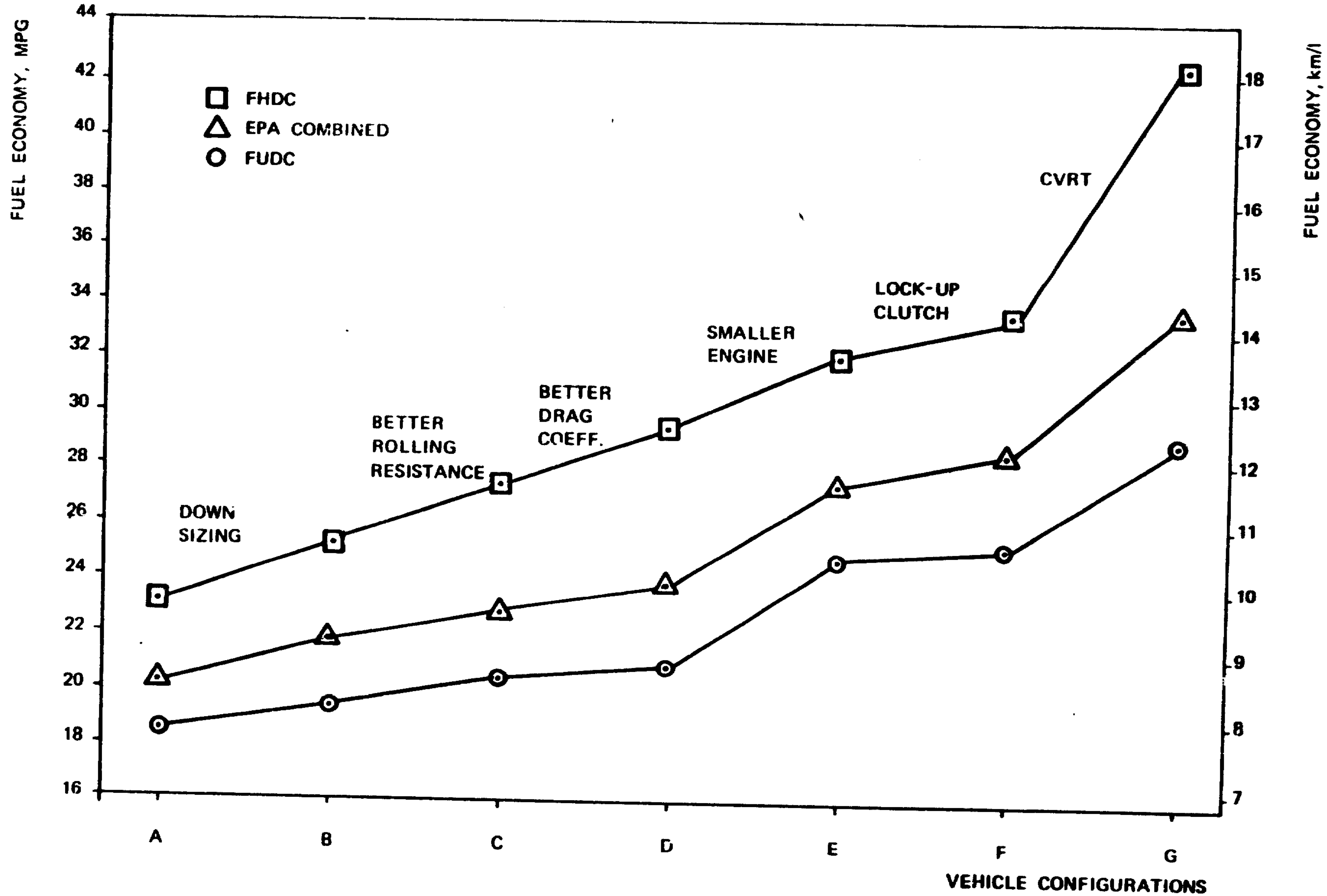


FIG. 5.1-1 PLOT OF FUEL ECONOMY AS FUNCTION OF VARIOUS CONVENTIONAL VEHICLE CONFIGURATIONS

an equivalent theoretical A vehicle for which the parameters that were not available have been derived from reasonable assumptions. A difference therefore results between the values in column A and those in column A*.

The various technological improvements on the vehicle's design parameters were assumed to be applied to the 6 cyl. 1978 Chevrolet Impala. The main characteristics of its propulsion system are outlined below:

- 3-speed automatic transmission	$\tau_1 = 2.52$
	$\tau_2 = 1.52$
	$\tau_3 = 1.00$
- final drive ratio	$\tau_d = 2.41$
- 11" Torque Converter without lock-up clutch	
- 250 CID Engine (4.1 l)	105 HP (SAE) at 3800 RPM
	(185 lb.ft at 1200 RPM)
	23.6 kgm at 1200 RPM

- Configuration A - The significant design parameters are shown in column A of Table 5.1-1 as provided by the manufacturer's descriptive literature. In the other columns of the said Table other vehicle configuration characteristics are presented and the corresponding fuel economies are given in the lower portion of the table itself. The technological improvements for each of the other vehicle configurations are summarized below.

- Configuration B - Modifications are made to weight, aerodynamic drag coefficient, rolling resistance coefficient and front section area to obtain the percentage reductions given in the column. The corresponding overall improvement, in terms of fuel economy, is of the order of 6.9% for the EPA COMBINED cycle.

- Configuration C - Only the K_n rolling resistance coefficient has been improved, by a value of 43.7%, resulting in a 5% improvement on the EPA COMBINED cycle. On the average, a 10%

improvement of the K_n coefficient implies a 1.15% fuel economy improvement; overall, the improvement of the K_n coefficient results in a fuel economy improvement of 6.32%.

- Configuration D - A 25% improvement of the aerodynamic drag coefficient C_x is obtained, giving a 4.4% improvement on the EPA COMBINED cycle. On the average, for a 10% improvement of the C_x a corresponding 1.74% fuel economy improvement results; overall, the improvement of the C_x results in a fuel economy improvement equal to 6.54%.

- Configuration E - The engine cubic displacement is reduced by 26.8% and a modification is made to the final drive ratio τ_d, bringing it to 3.2; the corresponding fuel economy on the EPA COMBINED cycle is 14.7% greater than that of Configuration D. Performance characteristics satisfy minimum mission requirements.

- Configuration F - The torque converter is associated with a Lock-up clutch, making possible a further improvement fuel economy of the order of 2.9% on the EPA COMBINED cycle.

- Configuration G - This configuration adopts a CVRT in place of the automatic transmission used in the previous case, with a fuel economy improvement equal to 19,9% on the EPA COMBINED cycle, with respect to Configuration F. The overall improvement, taking into account all the technological factors, is equal to 65.8% with respect to the initial value.

Each improvement, as outlined above, is associated with an appropriate cost increments of the reference vehicle as a result of the addition of innovative components or more advanced technologies. Better rolling resistance tires and use of smaller engines in itself should not result in appreciable cost increases while "downsizing" and use of CVRT should result in a much higher

cost increase for a given fuel economy improvement than a better drag coefficient or use of lock-up clutch.

The cost estimates for the ICE reference vehicle, as performed during the Mission Analysis and Performance Specification studies, basically correspond to configuration F. They were not obtained from an extra cost estimate for each of the expected technical improvements but as a result of an average yearly "technology cost increase factor" of 5% (See Subsection 7.2 below). In 1978 dollars this would correspond, for the 1986 full size model year, to a \$ 2,920 price ⁃ g increase (close to 48%), including the effect of all safety related extra equipment additions as a result of the corresponding legislation to be enforced.

The expected fuel economy percentage improvements developed during the Mission Analysis and Performance Specification Task, and the evaluated ones described above, are summarized and compared in Table 5.1-2.

5.2 IMPACT OF DEVIATION FROM DESIGN GOALS ON VEHICLE PERFORMANCE

On the basis of information provided by subcontractors Pirelli [1] and Pininfarina [2], [3] as well of results obtained during the Preliminary Design effort the design values of the most relevant vehicle critical parameters related to tire rolling resistance coefficient, aerodinamic drag coefficient and vehicle weight ($K_n = 0.45$, $C_x = 0.3$, $W_v = 1765$ kg).

The tire rolling resistance coefficient K_r is the coefficient of the SAE formula which, at 70 km/h provides the same rolling resistance resulting from the formula commonly used by Pirelli [1].

Any changes in C_x, K_n and vehicle weight imply, evidently, changes in fuel consumption and also in acceleration times and

TABLE 5.1-2 – COMPARISON BETWEEN FUEL ECONOMY EXPECTED AND EVALUATED PERCENTAGE IMPROVEMENTS

PARAMETER	FUEL ECONOMY % IMPROVEMENT	
	MISSION ANALYSIS	"SPEC '78"
WEIGHT REDUCTION & A_f (MAIN SECTION)	10.50	3.47
AERODYNAMIC DRAG	4.00	6.54
ROLLING RESISTANCE	3.00	6.32
LUBRICANTS	2.00	–
ACCESSORIES	2.00	–
DISPLACEMENT	–	14.70
DIESEL (OR EQUIVALENT)	25.00	–
LOCK-UP CLUTCH	–	2.90
AUTOMATIC TRANSMISSION	10.00	–
CVRT	–	19.90
TOTAL IMPROVEMENT	69.30	65.80

vehicle maximum speed. The influence of these parameters on the resulting fuel consumption was investigated and the results are shown in the various diagrams that follow. For each individual parameter and for the various cycles under consideration (FUDC, FHDC and reference mission), the fuel economy versus range curves are evaluated in optimized control strategy conditions: the horizontal and vertical asymptotes represent respectively the fuel economy with infinite range and the maximum allowable range in electric-only traction. Changes in C_x from 0.3 to 0.4, in K_n from 0.45 to 0.7 and in weight (with reference load) from 1765 kg to 1965 kg, are considered. By utilizing the intermediate parameter values, a vehicle is delineated which represents a "compromise" configuration characterized by the following: $C_x = 0.35$, $K_n = 0.6$, weight = 1915 kg and which allows the simultaneous influence on fuel consumption of the three parameters to be evaluated.

The data relative to this analysis are given in Table 5.2-1 and in Fig. 5.2-1/9.

It is evident, from the diagrams and Table 5.2-1, that changes in parameters with respect to the nominal imply a reduction of the fuel economy and a reduction of the daily range, for a predetermined regulation of the propulsion group. In particular, under field regulation limit conditions, the horizontal asymptotes move downwards while the vertical asymptotes move to the left (electric-only traction).

Table 5.2-2 gives the vehicle characteristics, the fuel economy and daily range date for the "compromise" and the "nominal" vehicle (to which minimum parameter values correspond).

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(1) APPENDIX C Vol. II Appendices of PRELIMINARY DESIGN DATA PACKAGE - Appendix A.1-4 page A.1-51

(2) APPENDIX B Vol. I Final Report on TRADE-OFF Studies Sect. 4.2.1.7 p. 4-10, Sect. 5.1 p. 5-1 and 5-2.

(3) APPENDIX C Vol. III Appendices of PRELIMINARY DESIGN DATA PACKAGE - Appendix A.1-3 page A.1-32.

TABLE 5.2-1 a – FUEL ECONOMY SENSITIVITY ANALYSIS DUE TO THE VARIATIONS OF C_x, K_n AND WEIGHT ON REFERENCE CYCLES AND MISSION

VEHICLE PARAMETERS			α	FUEL ECONOMY ON THE CYCLE (MPG)			RANGE (mi)		
WEIGHT (kg)	C_x	K_n		FUDC	FHDC	MISSION	FUDC	FHDC	MISSION
1765	0.3	0.45	0	∞	∞	∞	75.52	81.92	80
			0.3	63.92	88.20	79.56	113.92	116.48	115.71
			0.5	51.20	71.12	64.00	170.24	161.28	163.74
			1	33.44	44.70	40.78	∞	∞	∞
1765	0.35	0.45	0	∞	∞	∞	73.08	75.9	75.13
			0.3	63.37	85.79	77.88	109.44	107.9	108.3
			0.5	50.53	68.34	62.09	162.56	148.74	152.45
			1	32.67	42.0	38.83	∞	∞	∞
1765	0.40	0.45	0	∞	∞	∞	70.66	70.4	70.53
			0.3	62.81	83.40	76.26	105.47	100.1	101.63
			0.5	49.80	65.72	60.22	156.03	138.0	142.72
			1	32.03	39.58	37.08	∞	∞	∞
1765	0.3	0.6	0	∞	∞	∞	70.66	75.14	73.86
			0.3	62.92	85.46	77.53	105.47	106.62	106.24
			0.5	49.87	67.97	61.58	155.9	146.94	149.38
			1	32.17	41.58	38.37	∞	∞	∞
1765	0.3	0.7	0	∞	∞	∞	67.71	70.91	70.02
			0.3	62.22	83.65	76.16	100.61	100.74	100.7
			0.5	49.02	65.89	59.99	147.84	138.75	141.23
			1	31.44	39.95	37.08	∞	∞	∞

TABLE 5.2-1b – FUEL ECONOMY SENSITIVITY ANALYSIS DUE TO THE VARIATIONS OF C_x, K_n AND WEIGHT ON REFERENCE CYCLES AND MISSION

VEHICLE PARAMETERS			α	FUEL ECONOMY ON THE CYCLE (MPG)			RANGE (mi)		
WEIGHT (kg)	C_x	K_n		FUDC	FHDC	MISSION	FUDC	FHDC	MISSION
1865	0.3	0.45	0	∞	∞	∞	72.32	80.0	77.7
			0.3	63.00	87.29	78.63	108.93	113.79	112.38
			0.5	49.64	69.80	62.54	163.2	157.18	158.85
			1	32.58	43.55	39.73	∞	∞	∞
1915	0.3	0.45	0	∞	∞	∞	70.78	78.85	76.42
			0.3	62.52	86.81	78.14	106.5	112.38	110.59
			0.5	48.95	69.18	61.87	160.0	155.39	156.67
			1	32.19	42.96	39.21	∞	∞	∞
1965	0.3	0.45	0	(1)	(1)	(1)	(1)	(1)	(1)
			0.3	62.01	86.29	77.61	104.32	110.85	108.90
			0.5	48.26	68.53	61.19	157.06	153.47	154.50
			1	31.80	42.35	38.68	∞	∞	∞

(1) A 200 kg INCREASE IN WEIGHT WITH RESPECT TO THE REFERENCE WEIGHT RESULTS IN A "CRITICAL" VEHICLE, OWING TO INSUFFICIENT POWER BEING AVAILABLE ON THE CYCLES. AS FROM THE ASSUMPTIONS THE RANGE CORRESPONDING TO ELECTRIC-ONLY TRACTION HAS THEREFORE NOT BEEN CONSIDERED.

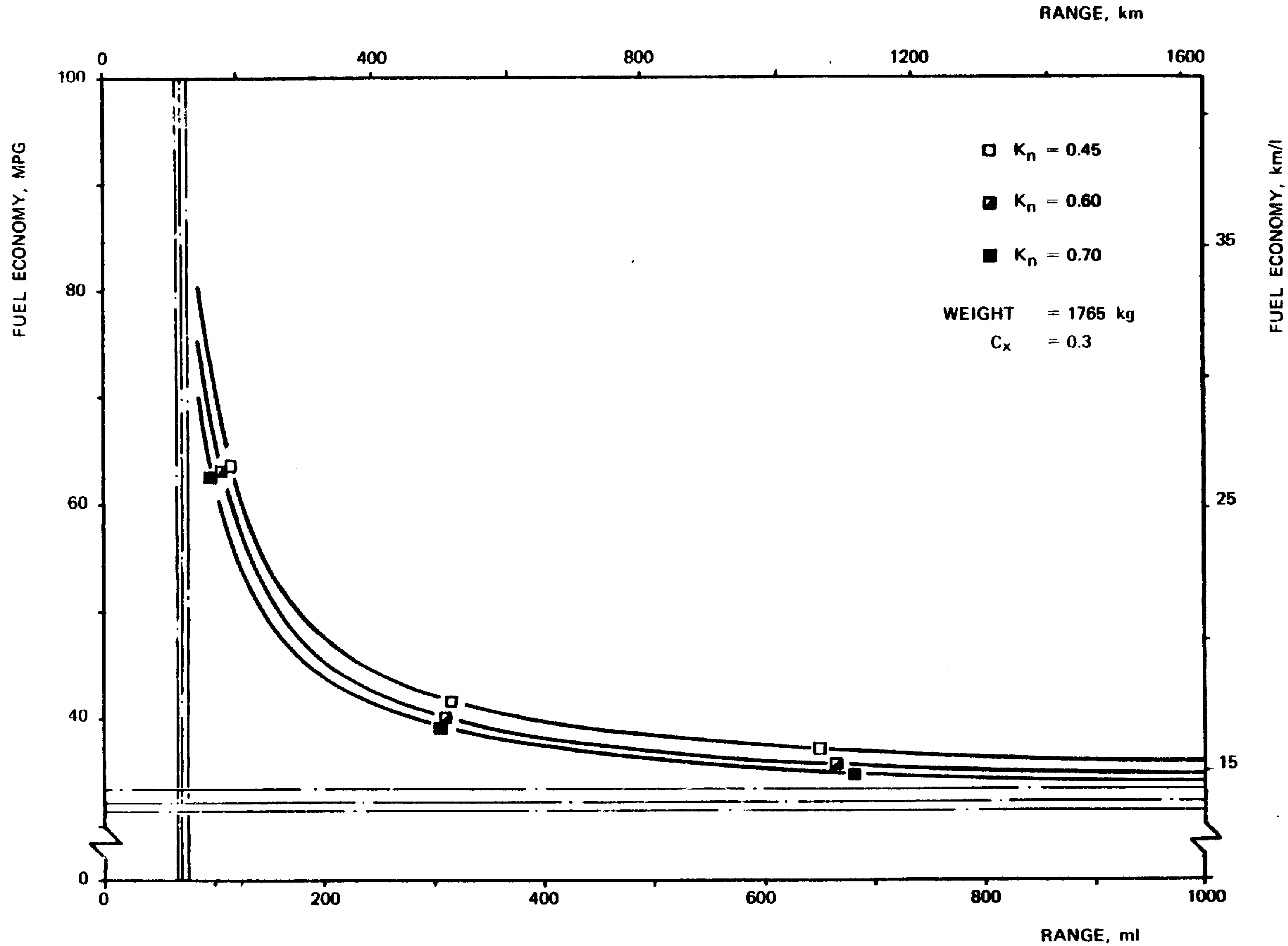


FIG. 5.2-1 FUEL ECONOMY VS. RANGE AS A FUNCTION OF TIRE ROLLING RESISTANCE ON THE FUDC

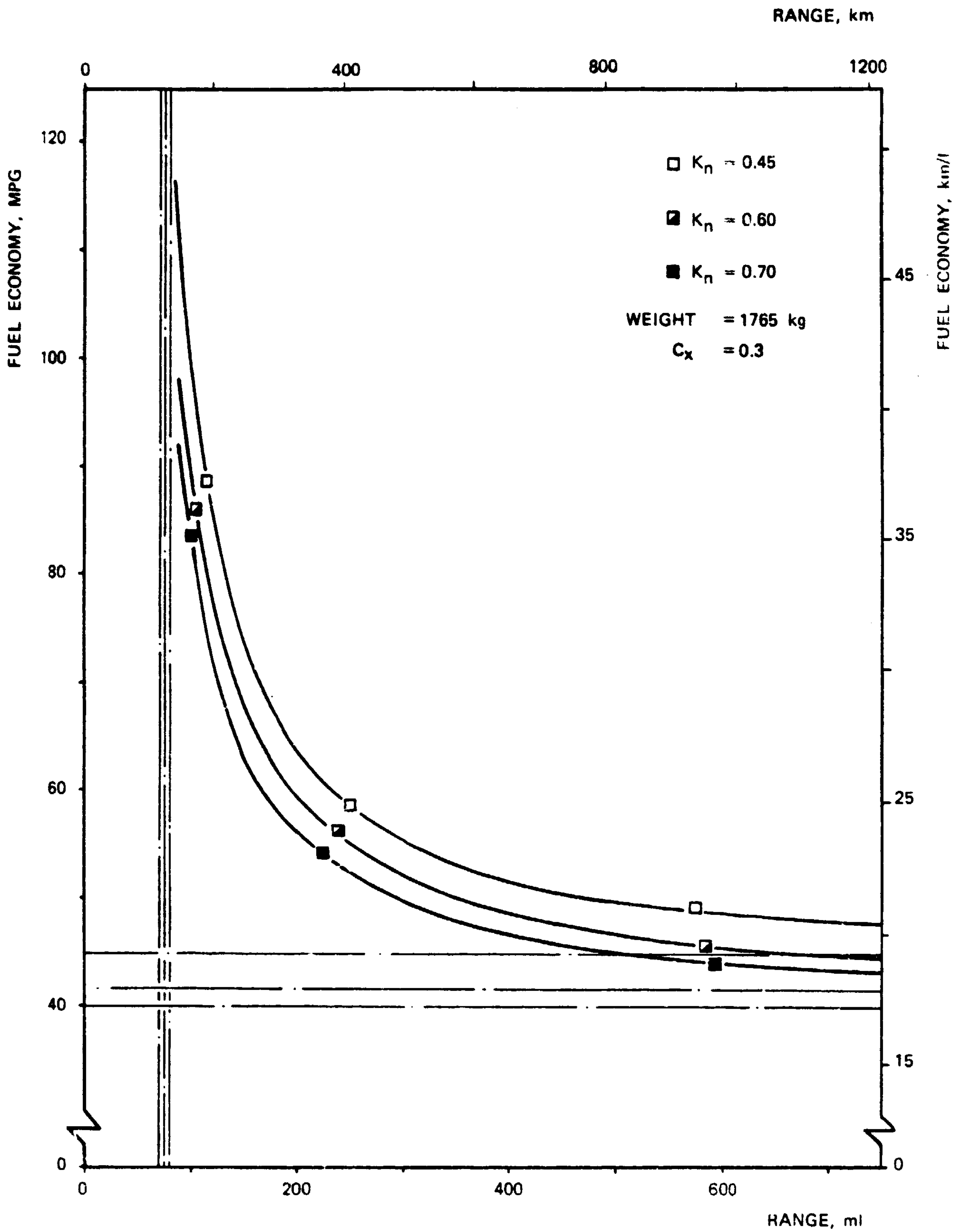


FIG. 5.2-2 — FUEL ECONOMY VS. RANGE AS A FUNCTION OF TIRE ROLLING RESISTANCE ON THE FHDC

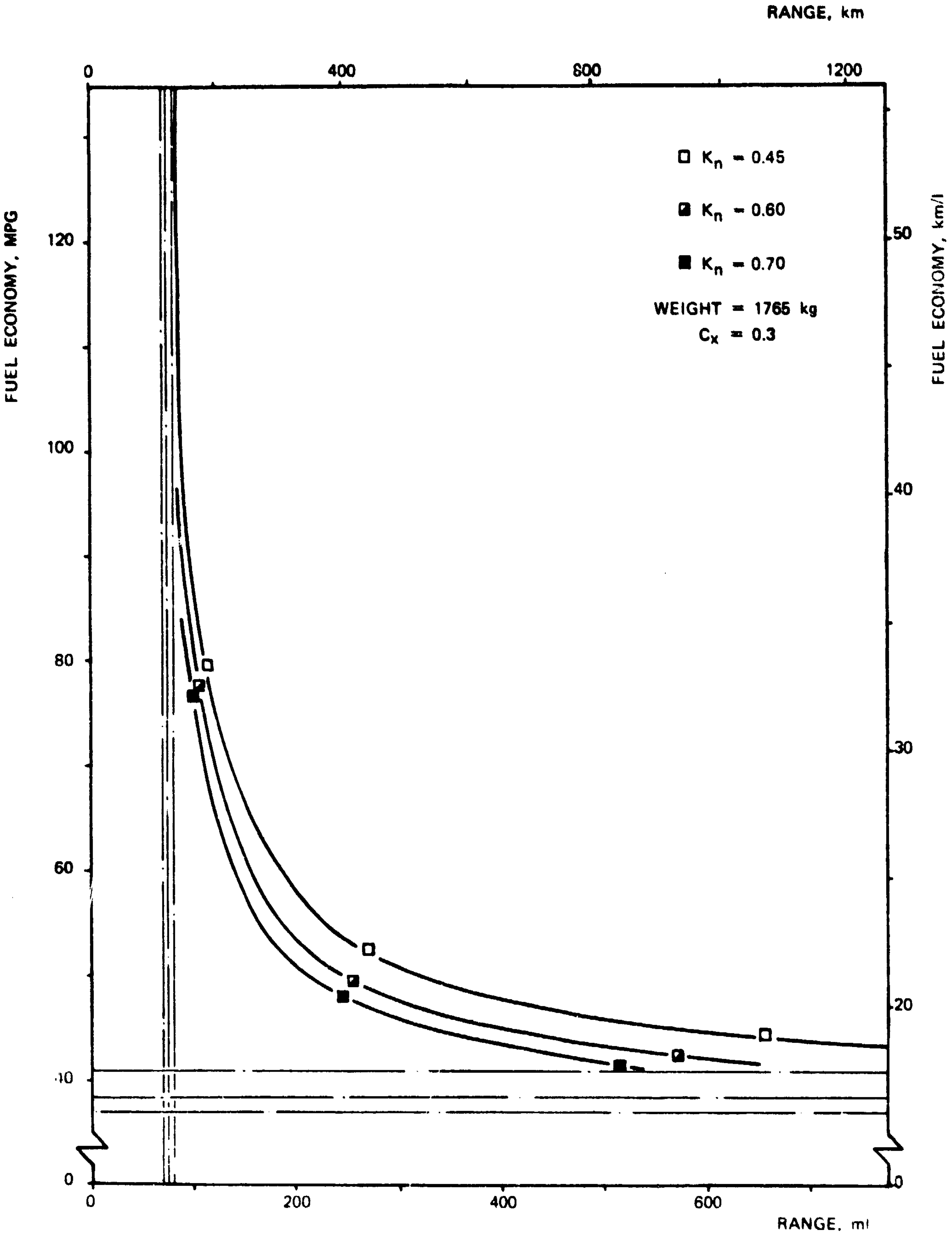


FIG. 5.2-3 — FUEL ECONOMY VS. RANGE AS A FUNCTION OF TIRE ROLLING RESISTANCE ON THE MISSION

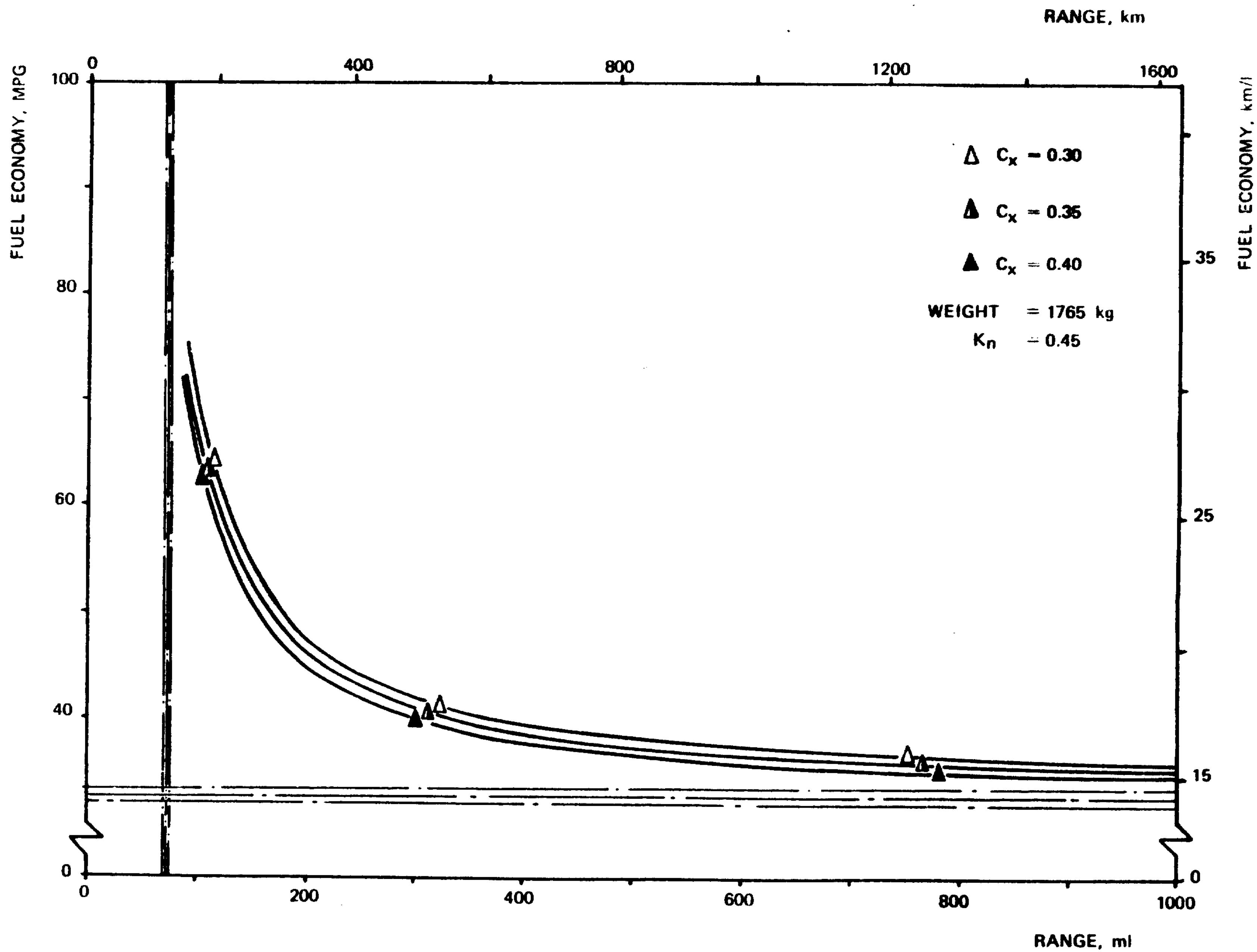


FIG. 5.2-4 FUEL ECONOMY VS. RANGE AS A FUNCTION OF AERODYNAMIC DRAG COEFFICIENT ON THE FUDC

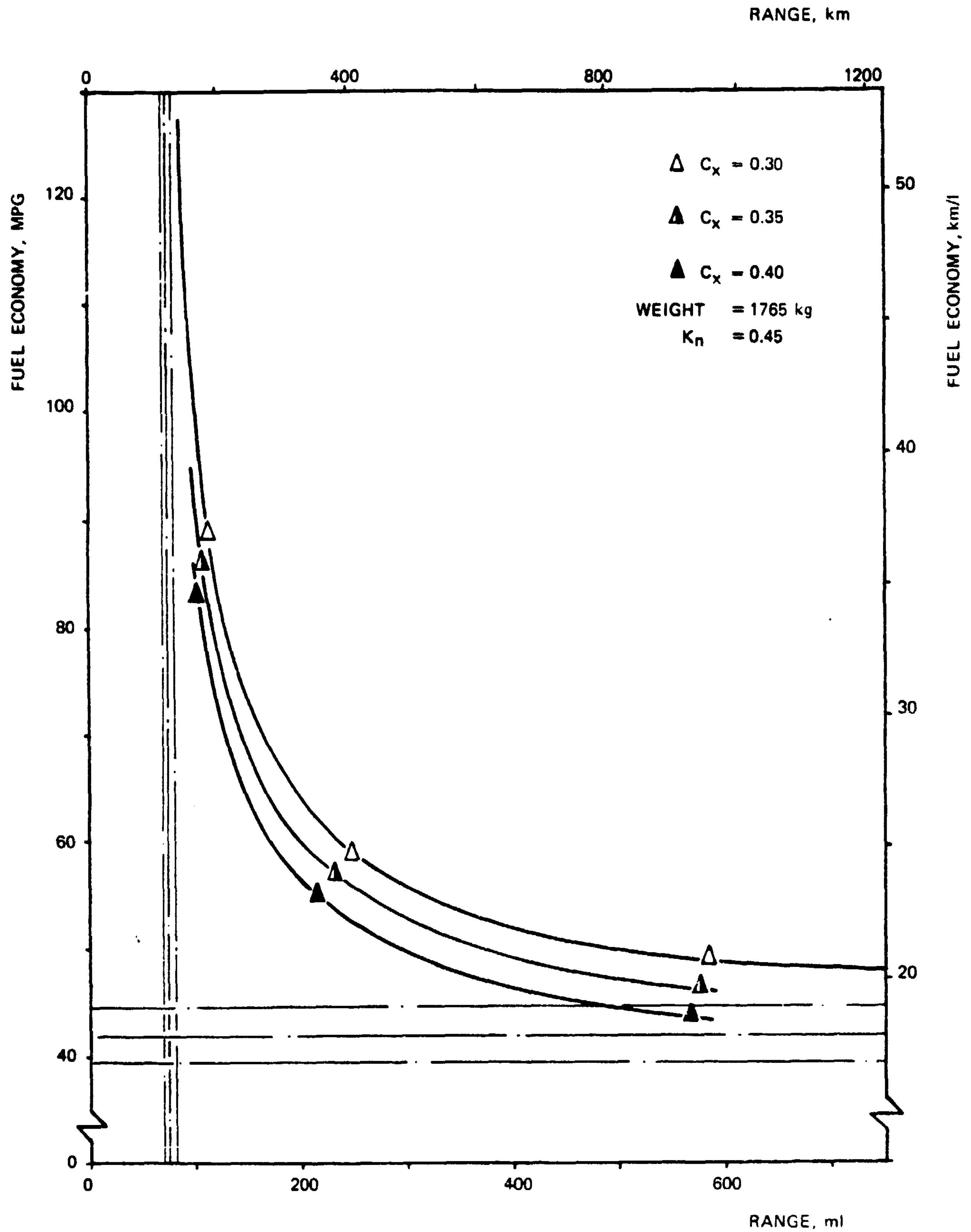


FIG. 5.2-5 — FUEL ECONOMY VS. RANGE AS A FUNCTION OF AERODYNAMIC DRAG COEFFICIENT ON THE FHDC

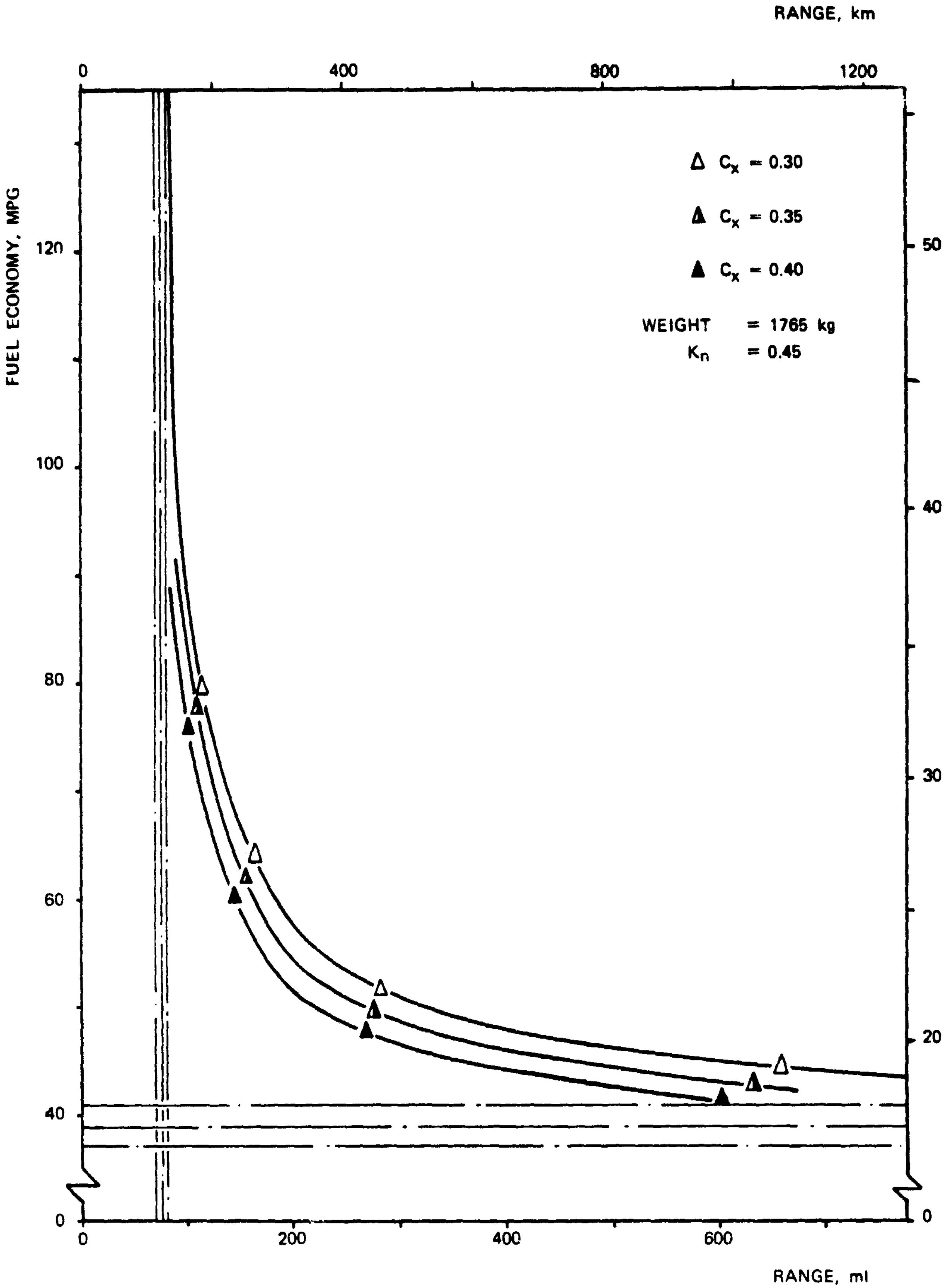
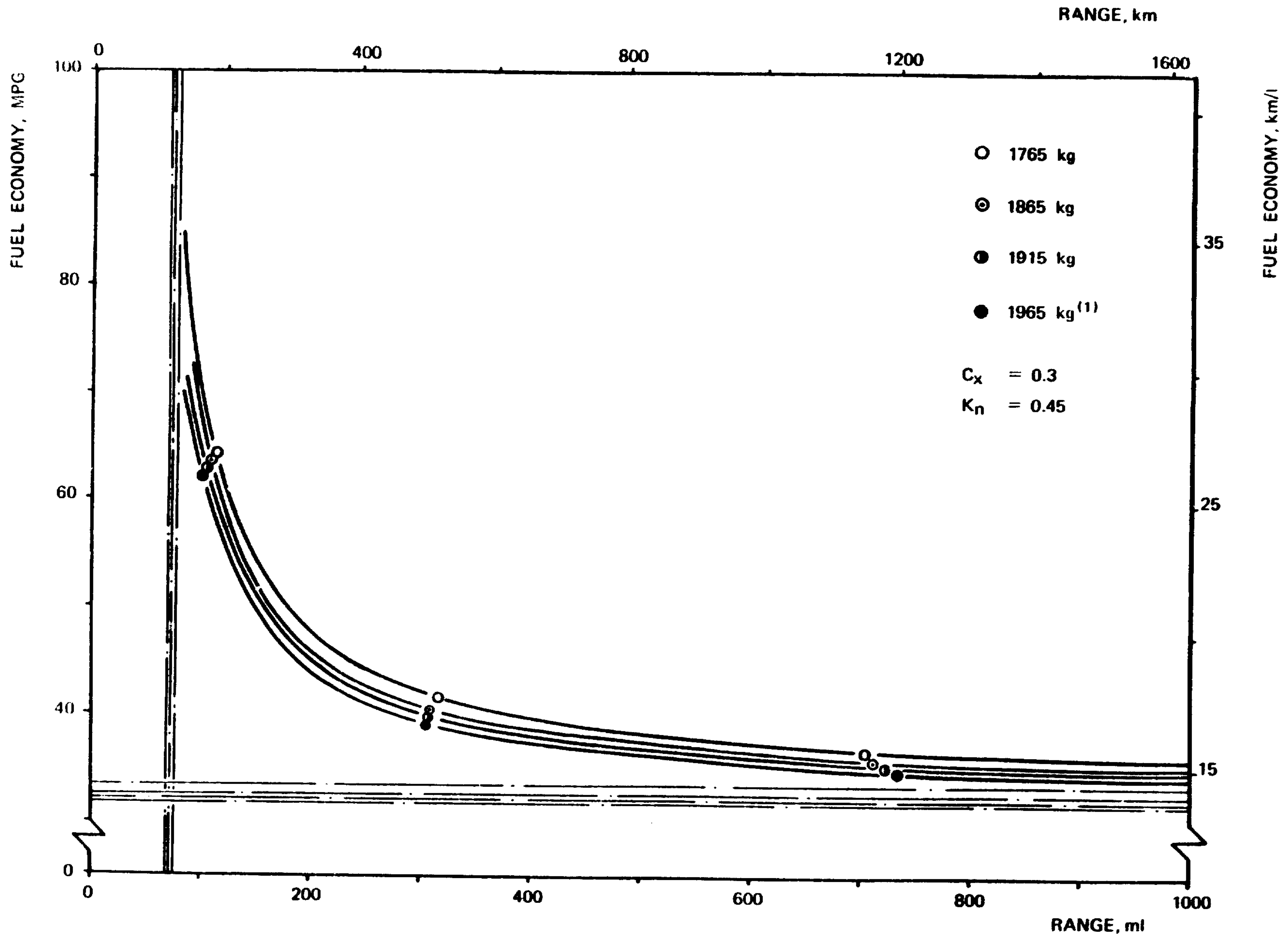
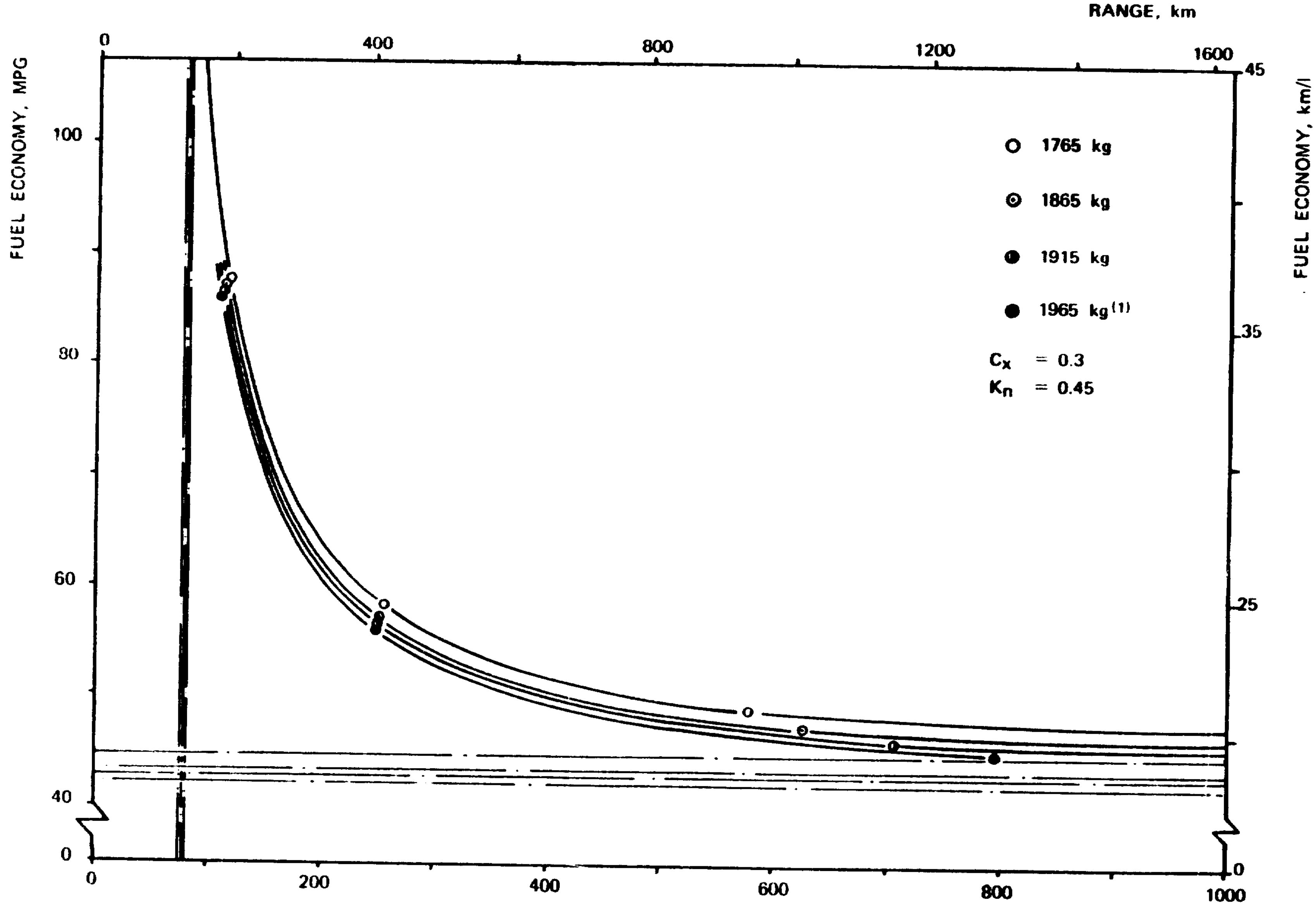


FIG. 5.2-6 – FUEL ECONOMY VS. RANGE AS A FUNCTION OF AERODYNAMIC DRAG COEFFICIENT ON THE MISSION



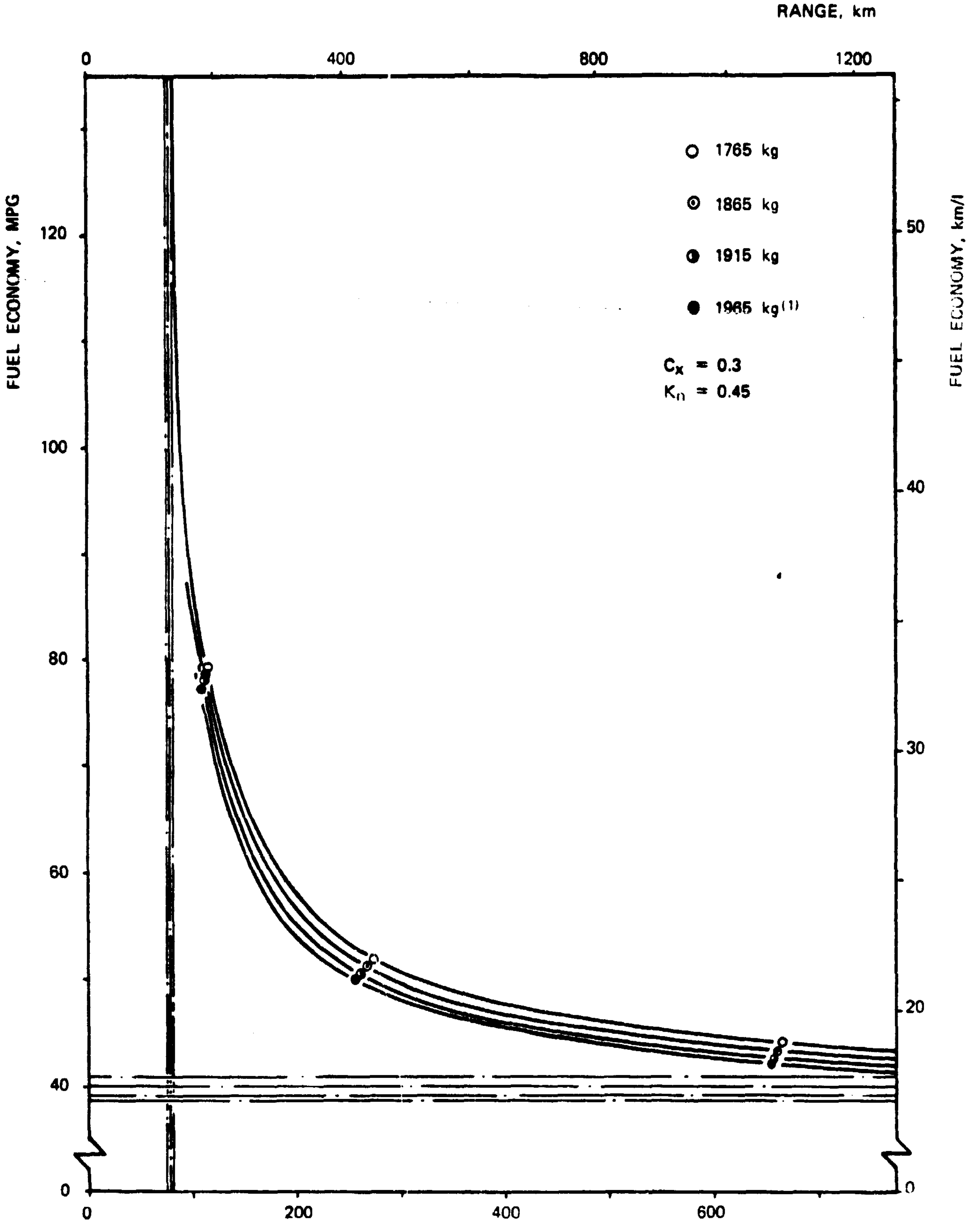
(1) THE CYCLE CANNOT BE PERFORMED USING ELECTRIC POWER ONLY

FIG. 5.2-7 - FUEL ECONOMY VS. RANGE AS A FUNCTION OF VEHICLE WEIGHT ON THE FUDC



(1) THE CYCLE CANNOT BE PERFORMED USING ELECTRIC POWER ONLY

FIG. 5.2-8 FUEL ECONOMY VS. RANGE AS A FUNCTION OF VEHICLE WEIGHT ON THE FHDC



(1) THE MISSION CANNOT BE PERFORMED USING ELECTRIC POWER ONLY

FIG. 5.2-9 – FUEL ECONOMY VS. RANGE AS A FUNCTION OF VEHICLE WEIGHT ON THE MISSION

TABLE 5.2-2 – COMPARISON BETWEEN "COMPROMISE" AND "NOMINAL" VEHICLES

VEHICLE PARAMETERS			α	FUEL ECONOMY ON THE CYCLE (MPG)			RANGE (mi)		
WEIGHT (kg)	C_x	K_n		FUDC	FHDC	MISSION	FUDC	FHDC	MISSION
1765	0.3	0.45	0	∞	∞	∞	75.52	81.92	80,00
			0.3	63.92	88.20	79.56	113.92	116.48	115.71
			0.5	51.20	71.12	64.00	170.24	161.28	163.84
			1	33.44	44.70	40.78	∞	∞	∞
1915	0.35	0.6	0	(1)	(1)	(1)	63.90	66.60	65.70
			0.3	60.76	81.52	70.27	95.10	94.72	94.85
			0.5	46.85	63.40	57.59	140.80	130.50	133.38
			1	30.43	37.70	35.29	∞	∞	∞

(1) ON THE FUDC AND THE FHDC CYCLES, THE "COMPROMISE" VEHICLE BECOMES CRITICAL OWING TO INSUFFICIENT POWER IN ELECTRIC-ONLY TRACTION; HOWEVER THE PERCENTAGE OF TIME DURING WHICH THE CYCLE CONDITIONS ARE NOT SATISFIED IS VERY CLOSE (1.7% ON THE FUDC CYCLE AND 1.9% ON THE FHDC CYCLE) TO THE LIMIT CONDITION (1.5%) INDICATED IN THE ASSUMPTIONS.
FOR THIS REASON THE ELECTRIC-ONLY TRACTION DAILY RANGE IS SHOWN, ALTHOUGH IT CAN ONLY BE CONSIDERED AS AN APPROXIMATE FIGURE.

Figures 5.2-10/12 show the comparison between the "compromise" and the "nominal" vehicle on the FUDC, FHDC and Mission cycles.

Performance characteristics of the solutions examined are given in Table 5.2-3.

5.3 CONCLUSIONS

The analyses carried out show that in order to meet 1985 fuel economy projections, conventional vehicles must mainly be modified in comparison with 1978 vehicles to achieve: - a lower drag coefficient - a lower rolling resistance - an optimum utilization of the spark ignition ICE (where applicable) - a lower weight.

The first objective can be achieved modifying body design, the second mainly by adoption of low rolling resistance tires and the third by using the ICE most of the time in the high load regime, which is possible by using smaller cubic displacement engines associated with CVRT. All these features have been incorporated in the concept of the hybrid vehicle; furthermore, optimum utilization of the ICE is obtained through the hybrid control strategy implementation.

With regard to the impact of deviation from design characteristics on vehicle performance, the analyses performed show that a "compromise" vehicle, differing from the "nominal" one (based on the preliminary design) in drag factor (0.35 instead of 0.30), rolling resistance (0.6 instead of 0.45) and loaded weight (1915 kg instead of 1765 kg), would still achieve a fuel economy largely exceeding that of the 1985 reference vehicle, while meeting at the same time most of the JPL Performance Requirements.

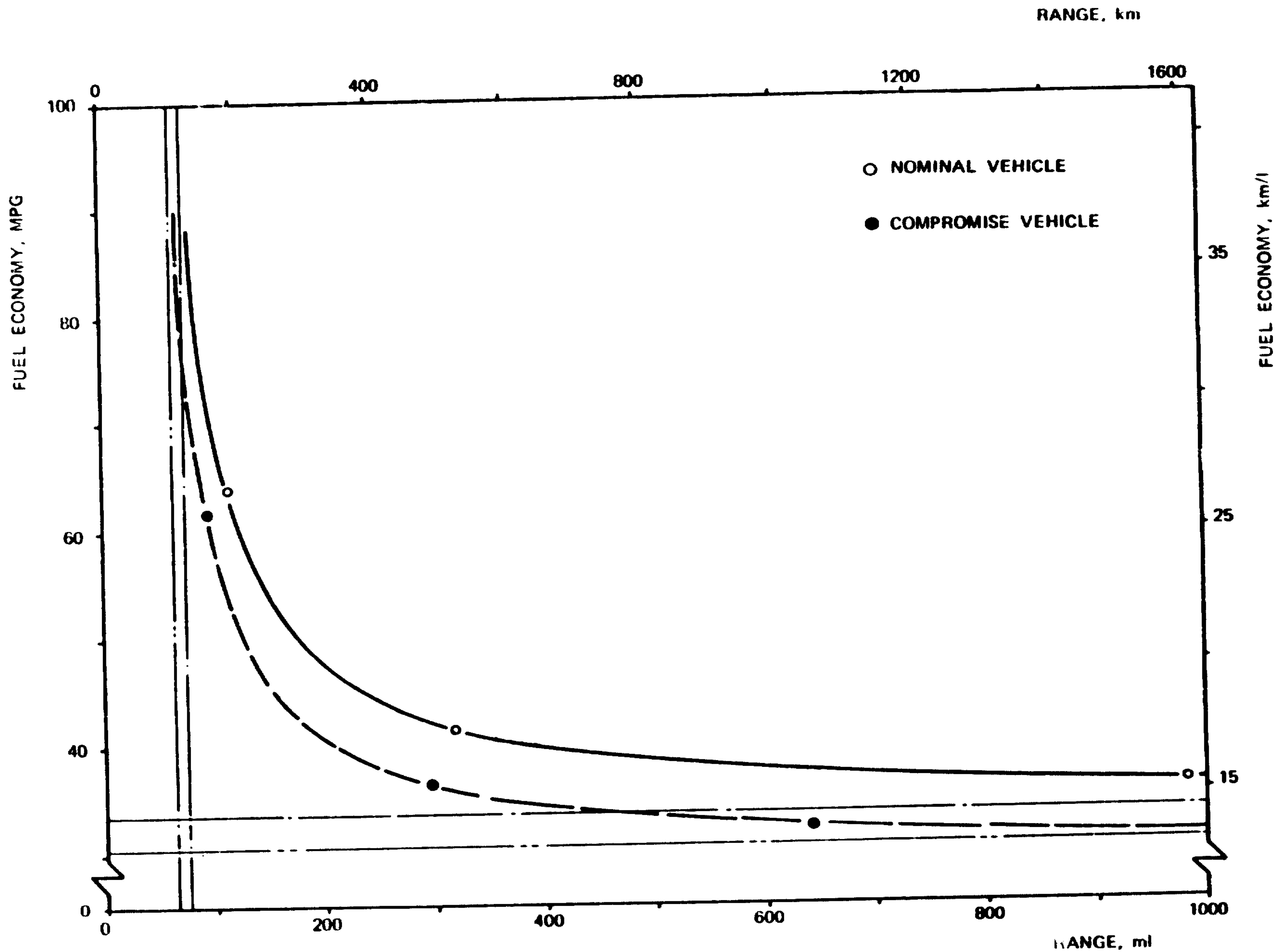


FIG. 5.2-10 – FUEL ECONOMY VS. RANGE ON THE FUDC:
COMPARISON BETWEEN "NOMINAL" AND "COMPROMISE" VEHICLES

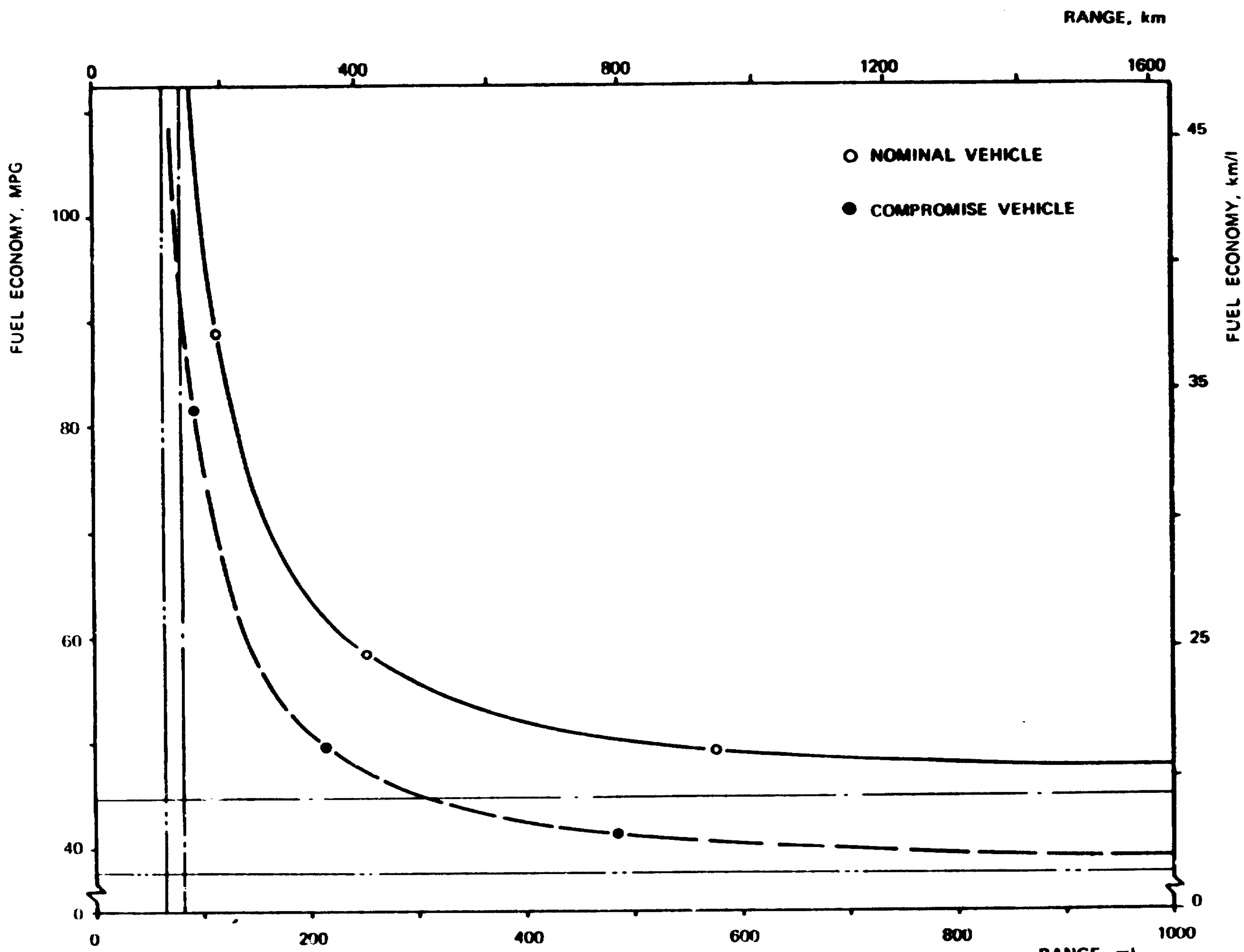


FIG. 5.2.11 — FUEL ECONOMY VS. RANGE ON THE UDC

... AND ... VEHICLES

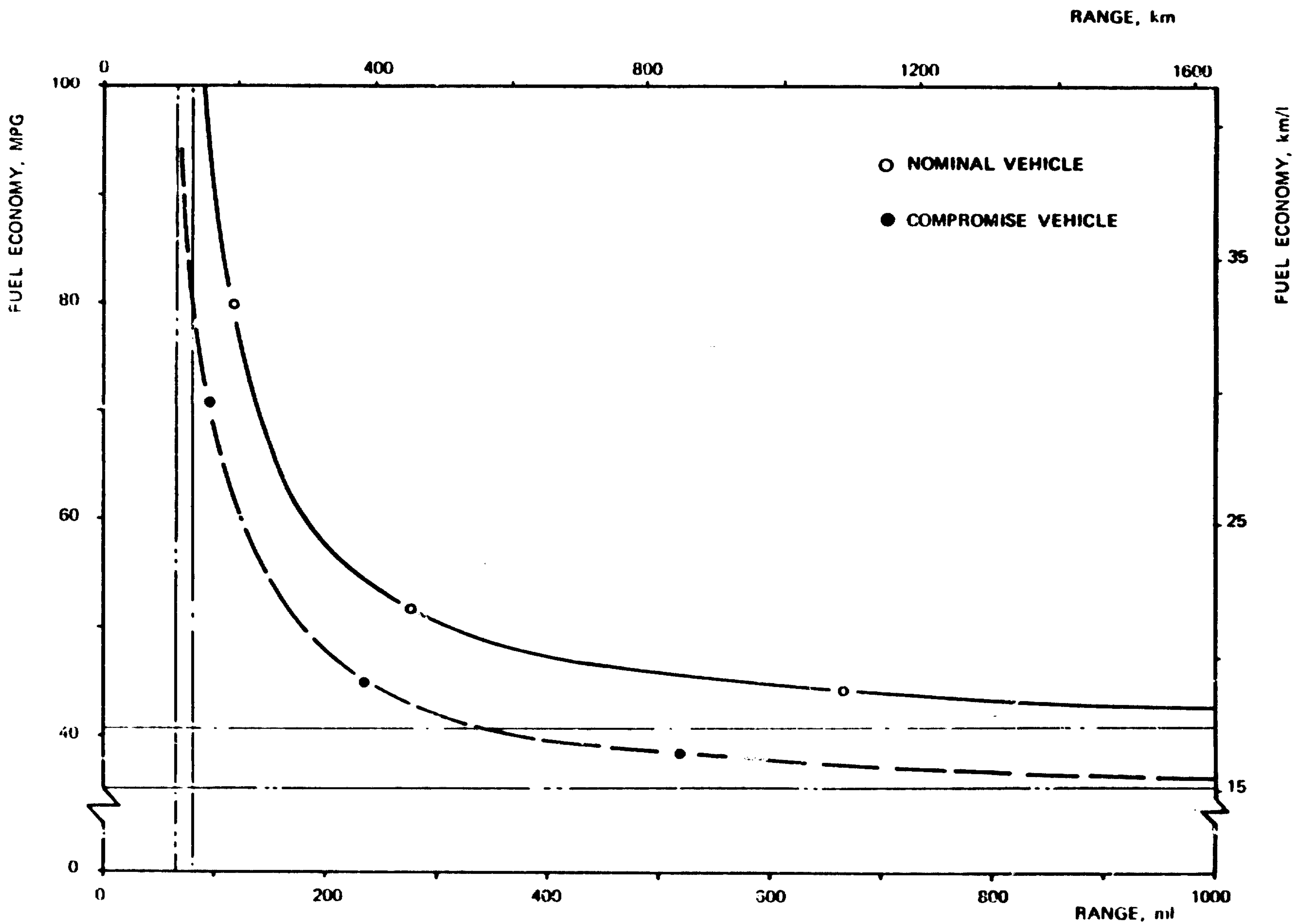


FIG. 5.2-12 — FUEL ECONOMY VS. RANGE ON THE MISSION: COMPARISON BETWEEN "NOMINAL" AND "COMPROMISE" VEHICLES

TABLE 5.2-3

COMPROMISE VS. NOMINAL VEHICLE PERFORMANCES

VEHICLE TYPE	SPEED km/h	ACCELERATION TIME (1)		
		0-50 km/h (s)	0-90 km/h (s)	40-90 km/h (s)
NOMINAL	136.31	5.48	13.82	9.51
COMPROMISE	126	5.97	15.31	10.63

(1) MINIMUM REQUIREMENTS: 0-50 6s; 0-90 15s; 40-90 12s.

C-2

SECTION 6

COMPUTER SIMULATION MODELS UTILIZED

Besides the well known Computer Codes Nastran and Adina, the following Computer programs, previously implemented at FIAT, have been utilized:

1) SPEC '78
2) HANDLING
3) CURVMAGN
4) CURVMAGNCAR
5) PRESTMCC

This section provides a brief description of the programs listed above.

For further information, the following references are provided:

- SPEC '78: Appendix B - "Trade-off Studies" Vol. II, Appendices pages A.3-1/-30
- HANDLING: Appendix C - "Preliminary Design Data Package" Vol. II, Appendices pages A.3-1/-48
- CURVMAGN: Ibid. page A.3-49
- CURVMAGNCAR: Ibid. page A.3-50
- PRESTMCC: Ibid. page A.3-51

6.1 "SPEC '78" COMPUTER SIMULATION MODEL

The mathematical model under consideration (SPEC '78) was implemented in 1978 to provide a powerful design tool for the evaluation of performance, consumption and emissions of any type of vehicle using any combination of components in the propulsion system.

The model can now simulate most common propulsion systems, being designed in such a way that the simulation of any new propulsion system can be easily added to the basic program.

The program consists of mathematical simulations of any vehicle component and external environment effects: internal combustion engine, transmissions (manual/auto/continuously variable), differential, rear-axle ratio, any mechanical connection group (gear or chain reduction group, joints etc....), electric motors and controls, battery performances, aerodynamic drag, rolling resistance etc. An appropriate code is used to identify any specific propulsion system consisting of a given configuration and using specific components. A second identification code is used to label the system control logic.

The model, on the basis of input design parameters, calculates the vehicle performance parameters on a time base related to defined initial operating conditions.

The time base comprises a sequence of discrete time steps, corresponding to cycle points of the simulated mission, which can be varied from 1 ms to 1 s.

The traveled distance is then obtained as the integral of the speed vs. time function.

The program input data consist of vehicle code, propulsion system code and mission parameters. The program output data consist of performance, consumption and emissions achieved in the simulated mission. The program is also able to show the efficiency breakdown at component level.

The values of any variable under evaluation can be given, if required, at intervals not longer than 1 second.

The mathematical simulation used by C.R. FIAT was validated by other calculation methods and experimental data for conventional propulsion, hybrid and electric vehicles.

6.2 HANDLING

The mathematical model is characterized by 11 d.o.f. (degrees of freedom) distribuited as follows:

- 6 d.o.f. associated with the body, considered as a rigid body in which the overall sprung mass is included. They are the 3 body center-of-gravity translations and the 3 body rotations (roll, pitch, yaw)
- 4 d.o.f. associated with the angular velocity of each wheel since different slip ratios are possible
- 1 d.o.f. associated with the steering wheel angle. This degree of freedom exists only for those maneuvers in which the steering wheel is released.

The main input data required by the program are the following:

- vehicle geometry
- sprung and unsprung mass
- moments of inertia
- geometric, kinematic and elastic characteristics of the suspensions
- braking system characteristics
- steering system characteristics
- transmission characteristics (gear, final ratio, torque converter, etc.)
- tire characteristics
- propulsion system characteristics
- aerodynamic parameters
- maneuver data.

In the framework of the main characteristics, the simulation mathematical model:

- performs a simulation of a vehicle (not necessarily of a symmetrical behaviour) with any of the four wheels driving, or braking, or both

- takes into account the non-linearity of the suspension and estimates its longitudinal and lateral displacements
- can deal both with independent suspensions and rigid axles, thereby taking into account effects due to possible anti-pitch and/or anti-roll rods
- as far as tires are concerned, considers the non-linear relationship between lateral forces and slip angles, normal load and tractive forces. Moreover, it estimates camber forces and aligning torques. Vertical and lateral tire flexibilities are however neglected
- assumes that the central moments of inertia of the vehicle remain constant during any motion: the interaction of those parts that change position during the maneuver is therefore neglected
- takes into account automatically the aerodynamic effects due to the vehicle speed
- can introduce external disturbances such as wind gusts from any direction and external forces and/or torques applied to the center of gravity
- neglects any effect connected with an irregular road-bed or the lifting of a wheel from the ground.

The model can simulate all "open-loop" tests (free path). Among these are the following:

- steering-pad
- steering wheel angle input
- throttle release
- balanced or unbalanced braking during directly forward or cornering motion
- external disturbances
- overtaking (only if steering wheel angle recording is available).

6.3 CURVMAGN

The CURVMAGN program provides the values of the various magnetic parameters in the different sections into which the magnetic circuit of the DC electric motor is divided. The no-load magnetization curve is plotted once the geometrical parameters of the magnetic circuit, and the magnetic characteristic curve of the laminations and of the iron used are known. Also obtained is the Lehman diagram, at no-load relative to the salient pole and assuming the necessary approximations for those non-linear magnetic phenomena involved.

Simulation of the magnetization curve of a DC electric motor has proved to be reliable, after comparison with that obtained from the experimental data relative to a DC compensated electric motor.

6.4 CURVMAGNCAR

The CURVMAGNCAR program provides the values of flux distribution in the air gap and draws, by means of a plotter, the magnetization curve under load conditions for all the values of current considered. The program requires knowledge of the magnetic circuit parameters, the magnetic characteristic of the laminations, the Lehman diagram at load relative to the salient pole, the degree of compensation and the excitation of the auxiliary poles.

6.5 PRESTMCC

The PRESTMCC program provides the mechanical power versus motor speed curves, both in motoring and in generating conditions, at different values of armature current. The program requires knowledge of supply voltage, and geometric and magnetic parameters of the electric motor.

Furthermore, this program provides the efficiency map of the DC motor/generator.

SECTION 7

ECONOMIC ANALYSES AND CONSIDERATIONS

7.1 INTRODUCTION AND SUMMARY

It has been stated, earlier in this report, that the proposed hybrid vehicle should have a competitive purchase price and a life cycle cost equal to that of the reference vehicle. This section describes the analysis performed to establish the purchase price and operating costs for the reference 1985 vehicle as well as the production cost and operating costs for the proposed hybrid vehicle.

The results of the cost estimation performed show that the necessarily higher initial price of the hybrid is balanced by the lower cost of the gasoline and electric energy it uses, relative to the cost of the gasoline consumed by the reference vehicle on the life mission considered.

The impact of replacing conventional vehicles by hybrid vehicles on the U.S. energy scenario is also described.

7.2 REFERENCE VEHICLE COST ESTIMATION

Costs were estimated for the full size, general purpose vehicle. Two sets of these costs were prepared, representing respectively the average new 1985 vehicle and the optimum new 1985 vehicle. JPL guidelines were followed in preparing these costs.

The acquisition cost analysis was initiated by establishing a purchase price for a 1978 Impala with a V-8 305 CID engine and all the popular amenities included. The purchase price of $ 6,116 was increased, so as to relate to the mean vehicle in the selected class, by the use of a technology cost increase factor of 5 percent per annum. The basic price of the 1985 car was thus calculated to be $ 9,036 (quoted in 1978 dollars).

The sales tax was computed according to the JPL guidelines of 5 percent ($ 452) and the total of purchase price and sales tax was used to calculate the 4 year interest charge at 12 percent annual rate. The $ 850 interest per year, discounted

2 percent/year, results in a total interest charge of \$ 4,337. The useful life of the vehicle has been assumed to be 160,100 km or 10 years, whichever comes first, with 21,300 average annual travelled kilometers. In this case, the useful life is 7.5 years and the salvage value has been taken as zero. The sum of these figures determines the acquisition cost of \$ 13,825. Routine maintenance, repair and tire cost were determined from: Liston and Aiken, Cost of Owning and Operating an Automobile, DOT, 1977. The costs presented in this reference are in terms of 1976 dollars. Using a U.S. News and World Report, the inflationary effect for cars was determined to be 18.2 percent over the years from 1976 to 1978. The costs in the Liston report were escalated to take this inflation into account. The maintenance costs were taken over a 10 year period (160,100 km) and then redistributed over the 7.5 year life for the average new vehicle on the basic of annual mileage accumulation. These annual costs were expressed as fractions of the vehicle acquisition cost so that they could be applied to the acquisition costs of the 1985 vehicles in estimating the operating costs for them. The maintenance costs were also discounted 2 percent per year and the total cost was \$ 6,471.

The yearly cost for annual taxes, license and registration was set at \$ 33. These costs were discounted at the standard rate (2%) and came to \$ 240. The insurance costs were also calculated as per JPL recommendations: \$ 175 + 0.01% of the purchase price for each of the first 5 years and \$ 75 + 0.006% of the purchase price for the sixth year. The yearly cost for the initial period was \$ 215 and for the remaining years, \$ 129. The total, 2 percent discounted cost, came to \$ 1,343. The average on-the-road fuel economy used was 11.7 km/1 and with the 21,300 average annual kilometers driven, amounted to an annual fuel consumption of 1,820 liters. This corresponds to a life time total of 13,660 liters. The cost of the gasoline was calculated according to the JPL established procedure. The yearly costs used are:

Year	c/l	c/gal	Year	c/l	c/gal
1985	25.2	95.5	1989	28.5	108.0
1986	26.3	99.5	1990	29.0	110.0
1987	27.2	103.0	1991	29.5	111.7
1988	27.9	105.7	1992	29.9	113.0

The total discounted fuel cost for the 7,5 years was $ 3,519, making the total operating life cycle cost $ 11,573.

The total life cycle cost of the average new 1985 vehicle, purchase plus operating, is $ 25,398. On a yearly basis this amounts to $ 3,372 and on distance travelled basis: 24.5c/mile or 15.8c/km. The life cycle costs for the optimum new 1985 vehicle were calculated in the same manner as described for the average new vehicle. The purchase price of the vehicle was increased to $ 9,940 by the method described. The percentage maintenance costs were applied to the total acquisition cost of $ 15,286. The on-the-road fuel economy is 13.5 km/l so that a total of 11,920 liters of gasoline would be used in the useful life. The total operational cost is $ 11,783, making the total life cycle cost $ 26,989. The key cost figures for the two 1985 vehicles are presented in Table 7.2-1.

As far as the hybrid vehicle is concerned, the cost to the consumer must be compatible with the reference vehicle if it is to have any possibility of penetrating the market. The acquisition cost of the vehicle should be established on the basis of the new vehicle level, i.e., between $ 9,000 and 9,500. The total costs for the vehicle should not exceed the value of 15.6 cents per kilometer travelled. These costs will support the basic assumption that the hybrid vehicle may be introduced into the fleet without the need to consider consumer preference or consumer resistance.

TABLE 7.2-1
LIFE CYCLE COSTS: LARGE GENERAL PURPOSE VEHICLE (1)

ITEM	NEW 1985	OPTIMUM 1985
PURCHASE PRICE, $	9036	9940
SALES TAX, $	452	497
INTEREST, $	4337	4769
SALVAGE VALUE, $	0	0
A - ACQUISITION COST, $	13,825	15,206
TIRES, REPAIRS AND ROUTINE MAINTENANCE, $	6471	7123
ANNUAL TAXES, LICENSE AND REGISTRATION, $	240	240
INSURANCE, $	1343	1401
FUEL, $	3519	3019
B - OPERATING COSTS, $	11,573	11,783
C - LIFE CYCLE COST, $ (A+B)	25,398	26,989
D - LIFE—7.5 YEARS AND 100,000 MILES		
COST / YEAR, $	3378	3589
COST / MILE, ¢	25.4	27.0
COST / KILOMETER, ¢	15.8	16.8
E - ON-THE ROAD FUEL ECONOMY, mpg	27.7	31.8

(1) ALL COSTS DISCOUNTED AT 2% PER YEAR AND IN 1978 DOLLARS

7.3 HYBRID VEHICLE PRODUCTION COST ESTIMATION

The Hybrid Vehicle Production Costs analysis was accomplished as a result of a detailed investigation of the production cost of the individual parts and components.

The experience of C.R. FIAT in this field has been acquired in terms of production levels up to 2,000 model vehicles per day (as related to current FIAT manufacturing facilities and market penetration). This level can be considered to be in the range of large production volumes and therefore the available know-how can provide reasonable assurance of adequate methodology availability to obtain reliable and at the same time competitive cost estimates.

On the other hand we think that, to comply with production levels expandable, for the U.S. market, up to 4,000 vehicles per day, appropriate large scale production methods, techniques and work organization should be considered as mandatory requirements, in conjunction with adequate capability in forecasting and assessing the most suitable technology and materials among those available in the mid 80's.

The last consideration would specifically apply to the new and advanced components not used in conventional vehicles currently manufactured such as, traction batteries, microprocessor based control units, Continuously Variable Ratio Transmission etc. The corresponding cost estimates have been made by extrapolating the limited available data with specific support from subcontractors' expertise.

A final problem which had to be solved was the definition of the criteria to account for expected U.S. manufacturing costs, since all the analyses mentioned above were referred to FIAT manufacturing costs for Italy only.

The most appropriate procedure to obtain projected U.S. production costs was identified as follows:

a) Upon completion of the accurate cost analysis of the vehicle model in the FIAT fleet most closely satisfying the selected

hybrid vehicle characteristics, the resulting cost should be adjusted to reflect present small series FIAT production costs (as incurred today) and account for the appropriate U.S. mandatory equipment fitting as well as for the higher production volumes expected for the hybrid vehicles of the mid 80's.

This projected FIAT production cost of a mass produced conventional large size (U.S. type) vehicle can be referred to as X_1; its characteristics should compare with the corresponding vehicle identified during "Mission Analysis and Performance Specification Studies".

b) The production cost X_1 should be adjusted to identify the production cost X_2 of the corresponding hybrid version under the same manufacturing conditions.

This would define a cost (or price) ratio between hybrid and conventional vehicles of similar size and performance characteristics.

$$C_2 = \frac{X_2}{X_1}$$

c) Defining Y as the U.S. manufacturing cost of the vehicle identified by the Mission Analysis, the expected cost of an equivalent hybrid vehicle mass produced in U.S. factories is given by:

$$X_3 = C_2 \, Y$$

In support of the FIAT manufacturing cost estimates, the summary of FIAT Procedures and Regulations as used to assess expected production costs of existing models is given here below. These procedures have not been implemented in the hybrid vehicle cost estimates; they only represent the methodology applied to establish and update the exhaustive data, based on the costs of each individual part and manufacturing step, that has been used as a foundation of the production cost analysis performed.

7.3-1 FIAT Procedure For Mass Production Cost Estimation

As a first step all the vehicle parts and components are broken down into four main categories or "assemblies":

- Engine and Transmission
- Chassis
- Body Frame
- Electrical Equipment.

For each assembly the vehicle breakdown is further developed throughout the "GROUPS" and "SUBGROUPS" levels down to the "COMPONENT" level as shown on Figure 7.3-1.

- Component Cost Analysis

The manufacturing drawings of the various parts, components and subassemblies are analyzed to identify material characteristics and quality, dimensions, tolerances etc.

The production cost of the UNFINISHED PARTS is first calculated in kL/kg (or $/kg): the additional costs for FIRST PROCESSING and PARTS FINISHING are then added as appropriate, together with the current cost of standard parts from EXTERNAL SUPPLIERS.

- Labor Cost Analysis

The manufacturing drawings are then analyzed to identify the appropriate production cycles and define the cost effectiveness of production organization to reach the best compromise between the following objectives:

- Short manufacturing time
- Minimum manpower
- Simple production and tooling equipment.

A processing cycle, based upon the existing production requirements, is defined for the various components, which includes a list of the machinery and tooling to be used. Processing cycle and assembling times, as well as machine set-up time where appropriate, are identified step by step, so that optimal work sequence and timing can be obtained.

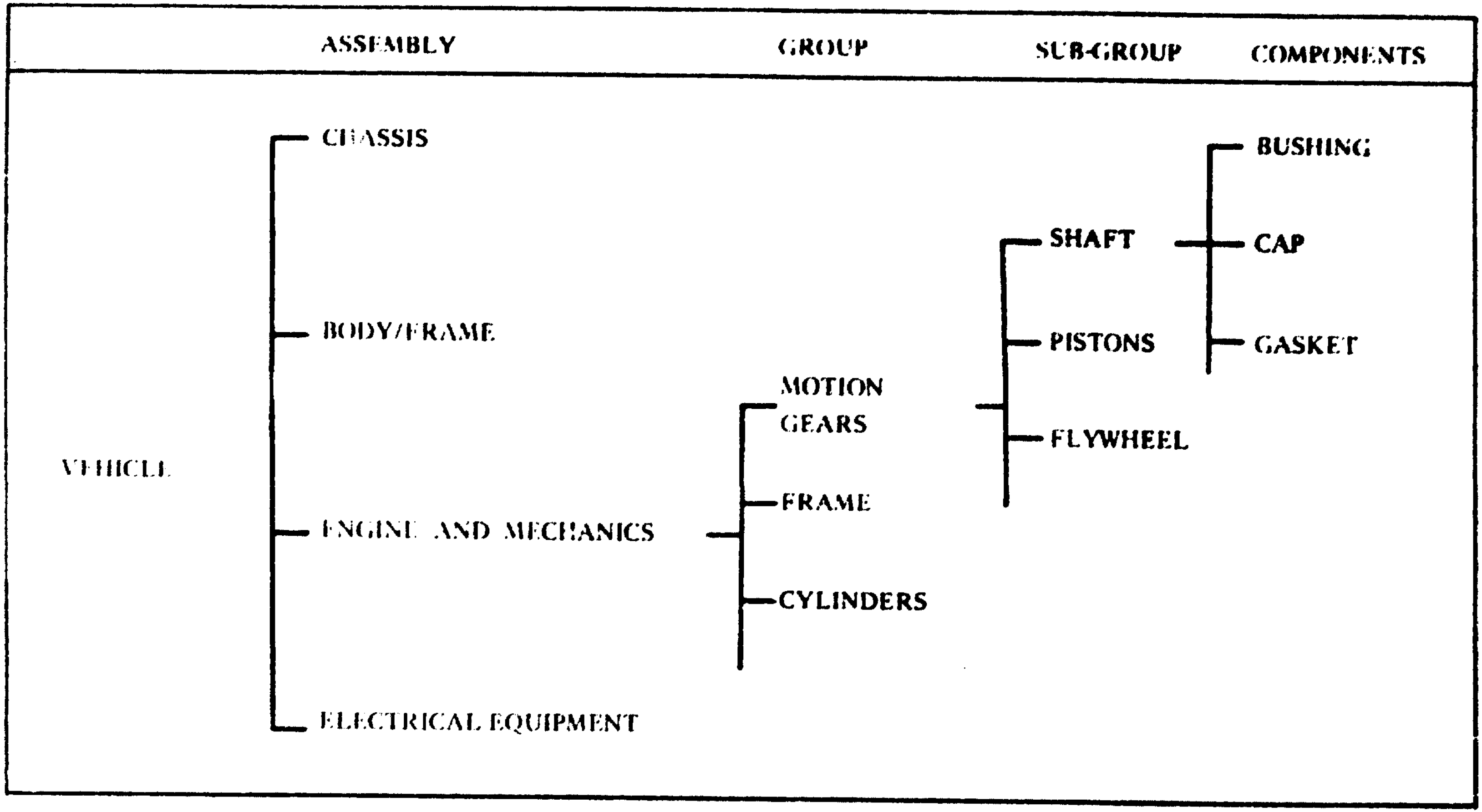


FIG. 7.3-1 – VEHICLE COMPONENT BREAKDOWN

Where small batch production is appropriate an assessment of the incidence of machine set-up on the total process cycle is made to determine the optimal batch size.

- Investments

On the basis of the expected cycle times and after evaluation of the effects of machine set-up, rejects, replacement and machine efficiency, the actual machine load is evaluated for the various parts. As a result the amount of equipment necessary to achieve the required production level and the corresponding value of the investment in assembly lines, machinery, fixtures, gauges and tools can be defined.

The plant size, number of workers and plant related services can therefore be identified, enabling the total investment value to be calculated. The projected construction and tooling machinery cost must be continuously updated using the established relationships with the various contractors ad suppliers.

- Manufacturing Cost

The projected manufacturing times are converted into manufacturing cost according to the projected average hourly labor rates, including both direct and overhead manhours.

The expenses resulting from general and specific investments are expressed as appropriate in yearly depreciation costs taking into account expected interest rates.

The total production cost is obtained by adding the total cost of parts and materials previously identified.

Based upon the number of vehicles to be produced on a yearly basis, the total vehicle cost can be accordingly defined, including an estimated additional cost to account for the improvements and design changes to be experienced during or after the first year of production.

7.3.2 Results of the Production Cost Analysis

The vehicle cost breakdown in 1978 U.S. $, determined according to the methodology described above, is shown in Table 7.3-1 for the selected alternative. The individual costs are intended to represent an estimate of U.S. manufacturing cost for mass production (> 1,500 units/day) of the Hybrid Vehicle components and/or subsystems.

The part lists for the various subsystems are given below. Production costs have been obtained for the conventional parts and components by projecting actual FIAT production costs of the LANCIA "GAMMA" to the expected 1985 production levels and technology. Labor costs for vehicle assembly have been attributed to the Chassis and Body/Frame Subsystems, according to current FIAT methodology and data availability. Adjustments to account for U.S. manufacturing have been only made at the total cost level using the procedure previously described.

Chassis Part List

- General assembly, organisation and workmanship
- Tank, fuel pipes and fasteners
- Transmission levers and tension rods
- Muffler, catalytic converter, pipes and fasteners
- Water tank, cooling liquid tank and pipes
- Steering knuckle, bearings, wheels, front and rear spacers
- Rear driving axle and bearings
- Propulsion system suspensions
- Front and rear suspensions: coil-springs, pins, track rods front and rear stabilizer bars
- Steering-wheel for power steering, steering box, steering arms and supports; oil tank, pipes and fittings
- Front and rear brakes
- Power brakes; box and fittings, pipes and controls and ancillary components
- Parking brake control and levers
- Hydraulic control system: pedal and supports, pump, brake fluid

TABLE 7.3-1

HYBRID VEHICLE PRODUCTION COST BREAKDOWN 1978 $ VALUE

ITEM	CONFIGURATION WITH Ni-Zn BATTERY
INTERNAL COMBUSTION ENGINE	358
CHASSIS (1) (2)	1098
BODY/ FRAME (1) (2)	1921
AUXILIARY ELECTRIC SYSTEM (1)	360
TRANSMISSION	225
ELECTRIC PROPULSION SYSTEM (1) (2)	700
POWER BATTERY	825
TOTAL COST	5487

(1) SEE SPECIFIC PART LISTS

(2) AS PRODUCTION COSTS ARE OBTAINED BY EXTRAPOLATION FROM ACTUAL FIAT PRODUCTION COSTS OF THE LANCIA "GAMMA", LABOR COSTS FOR VEHICLE ASSEMBLY ARE ATTRIBUTED TO CHASSIS AND BODY FRAME SUBSYSTEMS ACCORDING TO CURRENT FIAT METHODOLOGY AND DATA AVAILABILITY. ADJUSTMENTS TO ACCOUNT FOR U.S. MANUFACTURING ARE ONLY MADE AT THE TOTAL COSTS LEVEL.

supply tank, pipes,fittings and anti-skid braking system
- Electrical equipment controls
- Heater fan, pipes and controls
- Air Conditioner

Body-Frame Part List (includes Labor)
- Car assembly, mechanical drawings for type approval, drawings of the locking devices relative to the mechanical parts
- Body assembly and paint
- Front frame
- Lateral frame
- Roof panel frame
- Rear frame
- Inside panels
- External coating
- Floor
- Dashboard and relevant ancillary components
- Windshield and supporting components
- Side windows and ancillary components
- Rear window
- Front and rear doors and ancillary components
- Radiator
- Front and rear seats and ancillary components
- Battery supporting fixtures
- Vehicle lifting points
- Insulating panels
- Floor carpet and upholstery
- Trunk lid and ancillary components
- Front and rear integral bumpers
- Spare wheel installation
- License plates installation
- Radio installation
- Jack and toolholder
- External mirrors and filler cap cover

- Safety belts and gaskets
- Sealing, paint and enamel

Auxiliary Electrical System Part List

- Electric generator, starter motor, spark plugs
- Voltage regulators
- ICE starting battery
- External and internal lights
- Instruments and switches
- Windshield wiper and ancillary components
- Horn and fuses
- Emergency lights
- Electronic ignition system
- DC-DC converter

Electrical Propulsion System Part List

- Electric Motor/generator
- Reversible Power Conditioner
- Control unit
- On-board charger.

7.4 REFERENCE AND HYBRID VEHICLE LIFE CYCLE COST ESTIMATION

The Life Cycle Costs of the Hybrid and Reference ICE vehicles are shown on Table 7.4-1, which also provides an updated evaluation of the same reference vehicle cost items previously estimated and presented on Table 7.2.-1. The data presented in this Report pertains to the solution with a Ni-Zn battery as defined during the Preliminary Design Task.

The most important considerations in this area are the following:

a) Financing costs: basically consistent with the JPL Assumption and Guidelines, but more in line with current conditions, the annual percentage rate (12%) has been applied to the yearly

TABLE 7.4-1

HYBRID VEHICLE LIFE CYCLE COSTS 1978 $ VALUE (1)

ITEM	HYBRID VEHICLE	REFERENCE VEHICLE
PURCHASE PRICE (2)	10,974	9,036
SALES TAX (3)	549	452
INTEREST (4)	2,535	2,087
SALVAGE VALUE (5)	–	–
A – ACQUISITION COST	14,058	11,575
TIRES, REPAIRS AND ROUTINE MAINTENANCE	6,500	6,471
ANNUAL TAXES, LICENSE AND REGISTRATION (6)	240	240
INSURANCE (7)	1,468	1,343
FUEL (GASOLINE)	1,067	3,519
ELECTRICITY	404	–
BATTERY REPLACEMENT	–	–
SALES TAX ON BATTERY REPLACEMENT	–	–
INTERESTS ON BATTERY REPLACEMENT	–	–
B – OPERATING COSTS	9,679	11,573
C – LIFE CYCLE COST (A + B)	23,737	23,148
D – VEHICLE LIFE: 7.5 YEARS AND 100,000 MILES.		
COST/YEAR $	3,157	3,078
COST/MILE c	23.7	23.1
COST/KILOMETER c	14.7	14.4
E – TOTAL FUEL AND ELECTRICITY CONSUMPTION ON VEHICLE LIFE		
GASOLINE, gal	1,111	3,610
ELECTRICITY, kWh	12,503	–

(1) DISCOUNT RATE FOR PRESENT VALUE CALCULATIONS: 2% PRIVATELY OWNED – (2) 2.0 MANUFACTURING COST (3) 5% APPLIED TO PURCHASE PRICE – (4) 12% ANNUAL PERCENTAGE RATE (A.P.R.) FOR 4 YEARS APPLIES TO PURCHASE PRICE + SALES TAX – (5) THE ASSUMED LIFE MILEAGE OF 100,000 MILES ESTABLISHES A ZERO SALVAGE VALUE – (6) $ 33/YEAR – (7) $ 125 + 0.01 X PURCHASE PRICE (FOR FIRST 5 YEARS AND $ 75 + 0.006 X PURCHASE PRICE SUBSEQUENTLY).

average outstanding capital value (i.e. 12% of: 7/8 of the full capital, FC, for the first year; 5/8 of FC for the second year; 3/8 of FC for the third year and 1/8 of FC for the fourth year) for both the Hybrid and Reference ICE vehicles. The previous assumption was a 12% flat rate for 4 years on the total loan amount.

b) Salvage value: it was neglected for the conventional vehicle. For the hybrid vehicle a salvage value was actually attributed to the Ni-Zn battery accounting for its contents of valuable material (Ni) as well as its regeneration cost. It was however assumed more appropriate to extrapolate the hybrid vehicle cost with reference to a steady state condition by including in the initial vehicle cost the battery regeneration cost only and attributing therefore zero salvage value to the hybrid vehicle as well.

c) Fuel and electricity consumptions: for the hybrid vehicle a conservative assumption was made to reach the vehicle life of 160,100 km by only performing the daily cycle mission range (234 km with 38.1 km/l fuel economy) for a total of 684 daily missions (which is beyond the expected battery life of 400 cycles at 80% depth of discarge, DOD). This would result in a total fuel and electricity consumption of 4,205 liters and 45,010 MJ.

d) Battery replacement: since the previous assumption is conservative for fuel consumption assessment but is too pessimistic with respect to battery life (only the maximum allowed 80% DOD is considered) a more realistic assumption has been made which allows the use of the battery over the entire vehicle life. It has been assumed that the yearly total of 21,300 km is accumulated by performing every week:

   1. one 234 km daily-cycle mission in the hybrid mode but limiting the DOD to 40%; this would correspond to a fuel economy of 23.6 km/l.
   2. six 29.1 km missions in the electric-only mode with battery recharge every second day to account for the

fact that battery exploitation is improved if DOD before recharge is kept above 30%.

The above assumption results in a total of 1,560 40% DOD cycles as compared to the expected 1,600 cycle battery life. It must be pointed out that while the battery life now exceeds the vehicle life, the total fuel consumption would still be limited to 4,390 liters (3[illegible]1 liters less than under the previous assumption) due to the impact of electric-only driving.

e) Vehicle life: maintained at 160,100 miles (7.5 years) for both vehicles. This assumption also can be considered conservative for the Hybrid Vehicle which should be expected to have a longer life (up to 10-20% more) considering the better operating conditions of the engine and electric motor as well as of the body structure (less vibration induced fatigue and better rust resistance).

<u>Conclusions:</u>

- Under the assumptions made, the life cycle costs are very close to each other (the hybrid vehicle is only 2.5% higher) and, therefore, well within a reasonable tolerance range to be considered equivalent.
- A 25% gasoline cost increase with respect to the mid-boundary value would be sufficient to totally balance the estimated life cycle costs.
- The very limited difference in the life cycle costs of the two vehicles could be further reduced by considering the possible salvage value of the electric motor (up to 20 or 30% of its original value).

It can therefore be concluded that the Hybrid Vehicle as defined by the Preliminary Design meets the minimum requirements concerning the life cycle cost, with reference to the average vehicle use.

7.5 U.S. ENERGY SAVING

Assuming that conventional vehicles would meet the 1985 fuel economy standards, the annual petroleum-based fuel saving with respect to an equivalent conventional car would be 1,250 liters per vehicle; it would correspond to a total saving (for every 100,000 hybrid vehicles in the fleet) of 125×10^6 liters per year. Such a saving should be considered an "actual" one since the hybrid vehicle would effectively "substitute" equivalent size conventional vehicles rather than "be forced" into the market only to alleviate the CAFE requirements (as could happen with small size electric vehicles).

The life cycle energy consumption of the hybrid vehicle (374,012 MJ) compared to the reference one (587,497 MJ) is about 35% less.

SECTION 8

RELIABILITY AND SAFETY

8.1 RELIABILITY

The comparison between hybrid and conventional vehicle can be made considering that both vehicles use the same mechanical solutions and differ by:

- the additional components of the electrical power system (electric motor, power conditioner and battery)
- the possibility of the hybrid to drive in different modes (with electric-only traction, with hybrid traction with emergency thermal-only traction)
- the lower stress generally applied to the thermal power system (motor and CVRT) due to the fact that it is used seldom and only in optimised operating conditions.

The probability of failure of the above mentioned additional components and the impact on vehicle performance and/or handling capability are here below described.

- The Continuously Variabile Ratio Transmission

Electronic control of hydraulically actuated automatic transmissions has already been successfully implemented in Europe in production cars with significant improvements in flexibility (and therefore efficiency) and reliability.

Performing such a function in a subsystem of the sofisticated control system required by the hybrid vehicle should add in terms of reliability with respect to a stand-alone system.

As far as CVRT's are concerned rubber belt types have been, now, successfully in use for over a decade with satisfactory reliability results, provided the appropriate maintenance requirements are satisfied (rubber belt replacement every 20,000 km).

The new steel belt type proposed for the hybrid vehicle results from a FIAT development intended for planned production of conventional ICE passenger vehicles.

Because of the higher power handling capability requirements than previous rubber belt type applications, the design has resulted in a steel belt configuration which for ICE cars driven in a European environment is expected to provide a transmission life in excess of 100,000 km.

When used in the proposed hybrid vehicle to transmit the thermal power faction only in significantly less demanding conditions, the proposed transmission should largely exceed the vehicle life.

- The Electric Motor

The conventional D.C. motor selected is based on a mechanical commutator characterized by carbon contacts which are subjected to wear and should be substituted every 40,000 km, and a copper collector which should be polished every 80,000 km to prevent performance degradation.

The reliability of the specific motor chosen for this project cannot be given due to lack of statistical information. Experience with similar motors applied to other traction fields shows, however, that the mean range before failure greatly exceedes vehicle rated lifetime (7.5 years), if the above maintenance rules are applied.

- The Power Conditioner

The power conditioner is based on well tried components and experienced circuit configurations and can be designed to meet any reliability goal required. A reliability goal of 0.90 to 0.95 on the rated lifetime is considered realistic for this program.

- The Battery

The battery can fail to deliver the electrical power required for electric-only traction, or to deliver any electrical power, as a consequence of:

- manufacturing deficiencies
- normal degradation by aging.

Manufacturing deficiencies should be kept to a minimum by manufacturing quality control. They normally result in early failures which either are detected by acceptance testing before delivery or occur during the guaranteed time or range of the vehicle.

Degradation by aging is kept to a minimum by continuous active control of the traction battery by the OBC which prevents overstressing of the battery at any time. Catastrophic failure of the battery due to cell failure, misuse or failures in the power line is prevented by continuous double protection by OBC and peripheral devices such as fuses, thermodiodes, etc.

8.2 SAFETY

The proposed hybrid vehicle crashworthiness equals that of the reference vehicle and complies with FMVSS requirements. The steel frame of the body is in fact reinforced to bear the additional thrust of the battery during front crash and so prevent the battery leaving its compartment (between the rear wheels under the trunk) to enter the passenger compartment or be thrown onto the road to the danger of other users.

In comparison with a conventional vehicle the hybrid is characterized by additional hazard sources originating in the electrical power system, which are:

- the 96V electric power circuit
- the chemical aggressivness of the battery's alkaline electrolyte
- the possible evolution of H_2 and O_2 during battery recharge and/or cell reversal.

The 96 V electric power circuit is insulated from accessible conductive parts (which are anyhow out of the drivers reach) and electric shock hazard during operation could therefore occur only in the presence of a double insulation failure. During idle

periods the circuit is open and no hazard can occur. During battery charge, leaks from the charge circuit to the vehicle frame would be detected and result in the opening of the AC charge line by a circuit breaker. Leaks from battery cell terminals and bus bars to the vehicle frame are prevented by enclosing the battery within a sealed plastic container.

Diffusion of electrolyte in the trunk and vehicle compartment is prevented by:

- the centralized venting system which conveys residual electrolyte spray, transported by venting gasses, to the exhaust outlet of the vehicle
- the above mentioned sealed container.

Concentration of explosive venting gas mixture in closed volumes with consequent hazard risk is prevented by:

- conveying venting gasses out of the vehicle through a sealed collector and a flame braking device;
- ventilating the battery cells toward end of charge, thus washing away any gas which may have leaked out of the centralized collector plumbing.

SECTION 9

SOURCE AND REFERENCE INFORMATION

9.1 INFORMATION SOURCES

The pertinent reference material needed to perform the contract activities was obtained using the following modes of information retrieval and acquisition:

1) C.R. FIAT technical data files on vehicle components performance and characteristics
2) Library technical literature searches and retrieval
3) Information obtained from personal contacts (meetings or long distance phone calls from Phase I Subcontractors: Brown Boveri, M. Marelli, Pirelli and Pininfarina).

For the last item the following list of Design Review meetings, Telex and Subcontractors Final Report references is provided.

a) MISSION ANALYSIS

1) Reference Files

The first search mode accessed the information system of Lockheed Retrieval Services, the System Development Corp., and Battelle. The following computer files were searched by the IITRI librarian:

- Smithsonian Science Information Exchange
- National Technical Information Service (NTIS)
- SAE Abstracts
- PTS U.S. Statistical Abstracts
- PTS U.S. Annual Time Series
- Magazine Index
- EIS Industrial Plants
- Transportation Research Information Services (TRIS).

2) Library Literature

Literature searches were made at:

- IITRI Engineering Division Library
- John Crerar Library on the IIT campus
- Chicago Public Library
- The Transportation Center Library at Northwestern University, Evanston, Illinois
- Library of the Chicago Area Transportation Study.

3) Personal Contacts

In addition to the computer and library searches, many people were contacted in the third search mode, i.e., phone calls and/or personal visits. The people and organizations contacted in this manner for technical information and/or further leads were:

- Institute of Transportation Engineers, Arlington, VA
- Mr. Roy Bell, Chicago Area Transportation Study, Chicago, IL
- Mr. Don Berry, Northwestern University, Evanston, IL
- U.S. Weather Service
- U.S. Bureau of Census, Chicago, IL
- Mr. John McCue, City of Chicago
- Mr. Brian Johnson, Barton Aschman Assn., Evanston, IL
- Mr. Dick Hankett, City of Chicago, Department of Public Works
- Mr. John La Plant, City of Chicago
- Mr. Marty Bernard, Argonne Laboratory, Lemont, IL
- Mr. Donald Schwartz, State of Illinois, Department of Transportation
- Mr. Richard Lill, American Trucking Assn., Washington, DC
- Mr. Seppo Sillan, Federal Highway Administration, Washington, DC
- Mr. Gary Maring, National Highway Traffic and Safety Administration, Office of Highway Planning, Washington, DC
- Messrs. Anthony Kane, Dick Ledbetter and Dwight Briggs, Bureau of Motor Vehicle Safety, Washington, DC
- Mr. Jim Rutherford, Environmental Protection Agency, Ann Arbor, MI
- Mr. Roy Husted, Department of Transportation, Washington, DC

- Mr. Weaver, Motor Vehicle Manufacturers Assn., Detroit, MI
- Systems Technology Corporation, Hawthorne, CA
- Mr. Paul Abbot, Federal Highway Administration, Washington, DC
- Mr. Mort Oskard, Federal Highway Administration, Washington, DC
- Mr. Tom Hollowel, National Highway Traffic & Safety Adm., Washington, DC.

b) TRADE-OFF STUDIES

A - <u>Brown Boveri & Cie A.G.</u>

a) Design Review Meetings:

(1) HEIDELBERG, Jan 29, 1979

(2) TURIN, Mar 21, 1979 - CRF Meeting Report SRE - 023/79

(3) TURIN, Apr 27, 1979 - CRF Meeting Report SR 540-79

b) Telexes

(4) FEB 2, 1979 TWX - Data on 32 kW Na-S Battery

(5) APR 4, 1979 TWX - Data on 36 kW Na-S Battery

B - <u>(Fabbrica Italiana) Magneti Marelli S.p.A.</u>

Design Review Meeting:

(6) MILAN, Mar 12, 1979

C - <u>Pininfarina S.p.A.</u>

Design Review Meetings:

(7) TURIN, Jan 25, 1979

(8) TURIN, Feb 16, 1979

c) PRELIMINARY DESIGN

A - <u>Brown Boveri & Cie A.G.</u>

a) Design Review Meetings:

(1) HEIDELBERG, June 26, 1979

(2) TURIN, July 24, 1979

b) Final Report on the Phase I Subcontract No. ZFL/Li/Mar. July 19, 1979

B - <u>(Fabbrica Italiana) Magneti Marelli S.p.A.</u>

a) Design Review Meeting:

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